DEVELOPMENT OF IMPROVED SENSING

METHODS AND DEVICES

FOR STAGE CHECKOUT

CONTRACT NO. NAS8-11715

PART II

INFRARED MEASUREMENTS
IN REAL TIME

FINAL REPORT FOR
PHASE A

15 JANUARY 1965

APOLLO SUPPORT DEPARTMENT

DAYTONA BEACH, FLORIDA ● HUNTSVILLE, ALABAMA

ASD

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PART II

Infrared Measurements in Real Time

Final Report for Phase A

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Volume I (unclassified)
Design Studies of a Real-Time Infrared Measurements System

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I. INTRODUCTION

This report describes a design study undertaken by the General Electric Company under Part II, Phase A, of NASA Contract NAS 8-11715. This study was conducted for the Quality and Reliability Assurance Laboratory (QRAL) at Marshall Space Flight Center by the General Electric Apollo Support Department, Daytona Beach, Florida. A major portion of the technical investigation was performed by the General Electric Electronics Laboratory at Ithaca, New York. This study program was begun in July 1964 and completed in January 1965.

The purpose of this study was to investigate the feasibility of using an IR vidicon camera for real-time measurements of infrared radiation from electronic circuits and components. In conjunction, design specifications were to be determined for a prototype system utilizing an infrared vidicon.

The results of this study are included in two volumes. Volume I is unclassified; it describes the general requirements of an Infrared Measurements System and detailed requirements of individual system components. Volume II is classified confidential; it includes performance data on infrared imaging tubes developed by GE, RCA, and Westinghouse.

II. ABSTRACT

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This report describes an investigation of the concept of using an infrared vidicon camera system for real-time measurements of infrared radiation from electronic circuits and components. Investigations to determine the requirements of the overall system and of individual components of the system are described in Volume I. Design recommendations for a prototype infrared measurements system are also given. The overall system is described under the following headings:

       Functional concept

       Mechanical design concept

       IR vidicon camera

       Signal processing and display

       Optics

       Cryogenics

       Calibration source

Volume II is classified confidential and includes performance data on infrared imaging tubes developed by GE, RCA, and Westinghouse. The relationship between this data and overall system performance is also explored in Volume II. A bibliography of reports that contain information pertinent to IR techniques for circuit testing is included in Volume II.

III. SUMMARY OF PHASE A PROGRAM

A. Program Requirements

1. Contract NAS 8-11715

The purpose of this effort was to study the concept of using an IR vidicon, with suitable optics and electronics, to measure IR radiation from electronic circuits and components, and to develop design specifications for a prototype system capable of satisfying this requirement. Specific items which were to be studied are summarized below:

1) IR vidicon sensitivity taking into account practical emissivity values

2) Optical requirements. Optics should provide a range of adjustment to view areas from 1 in. to 1 ft diameter at distances from 1 to 5 ft

3) Optical filter requirements

4) Method of obtaining, on a monitor display, a visual representation of the IR radiation pattern viewed by the IR vidicon

5) Gating techniques for measuring the temperature of a specific portion of the scene selected by an operator

Techniques for achieving these requirements were discussed at various meetings conducted during the study. Guidance received from NASA representatives during the study program helped to clarify various contract requirements in terms of eventual system application. Helpful suggestions were made in several areas, a few of which are listed below:

1) System configuration

2) Cryogenics system

3) Detection sensitivity goals and components temperature range

4) Types of components and circuits to be tested

2. Additional Features

Discussions with NASA representatives during the course of the study indicated the desirability of investigating several areas not specifically mentioned in the basic contract. These investigations concerned the feasibility of providing additional features to improve the versatility of the prototype infrared measurements system. Three of the features investigated are described briefly below and in more detail in section V.

a. IR Optics for Viewing 1/8-in.-Diameter Microcircuits. A field of view covering 1/8 in. diameter requires a higher magnification than for the original field-of-view requirements. Ideally, a lens of this type could permit thermal inspection of very small areas on a microcircuit.

b. <u>Visual Viewfinder</u>. This feature would permit alignment and focusing of the IR camera before applying power to the circuit being tested. A primary advantage is that thermal transients can be determined during the circuit warmup interval.

c. <u>Feasibility of Sealing the IR Lens Against the Wall of a Vacuum Chamber</u>. This capability would permit IR measurements of circuits and components within a vacuum chamber. Although this procedure is possible, an alternative approach is recommended. This approach is to seal an IR transmitting window into the wall of the chamber, to permit moving the IR camera as desired for alignment and focusing.

B. Investigations

At the beginning of this program in July 1964 three infrared image tubes were considered potentially applicable to the infrared measurements system. These were:

1) GE IR Vidicon

2) RCA Iricon

3) Westinghouse Thermicon

It was apparent that selection of the most suitable imaging tube was a prerequisite to many other portions of this study. The requirements of the optics, electronics, and cryogenics were dependent on the type of image tube recommended. Therefore attempts were made to obtain documents containing data on image tube performance as early as possible. Although the amount of data obtained was rather limited, comparisons of the characteristics of the three types of tubes were possible. Based on these evaluations, it was decided that the GE IR vidicon possessed certain advantages for this program.

Performance data and evaluations of the three infrared imaging tubes are included in Volume II of this report. Attempts were made to compile this data as a preliminary report for submission earlier in the program. However, this was delayed in order to devote additional time to other aspects of the study. This performance data was reviewed with a representative of NASA-QRAL at a meeting in Ithaca, N. Y. on 10 December.

Selection of an IR imaging tube in September permitted investigations of other areas to proceed based on specific requirements. Preliminary optical investigations were begun in September. In October, preliminary specifications for two IR lenses were compiled and submitted to optical firms for quotations. One specification of subsequent interest was the spectral band requirement of 1.5 to 5.0 microns (μ). The short wavelength requirement was based on possible use of reflected energy in the 1.5- to 2.0-μ band for boresighting and focusing the IR camera before applying power to the test circuit. Contacts with optical firms revealed the probability that resolution requirements would not be met with optical materials which transmit over the 1.5- to 5.0-μ band.

Assuming an alternative method of boresighting and focusing could be devised, further analyses were conducted to determine what portion of the spectral band was most significant considering blackbody radiation, vidicon response, and optical filter

transmission. It was determined that the significant spectral band is the 2.6- to 4.1-μ region. Subsequent optical investigations were based on using 2.0 μ rather than 1.5 μ as a short-wavelength limit. Specifications for resolution were applied to the most significant spectral band (2.6 to 4.1 μ) for increased design feasibility. In December contacts with optical firms indicated that optical design requirements could be met and that use of a reflex sight for visual boresighting and focusing was feasible. Investigations of optics for viewing microcircuits and of techniques for using the camera to test circuits in a vacuum chamber were also conducted in December.

Investigations of cryogenics requirements were begun in October after the type of IR vidicon to be used was decided. Preliminary specifications were compiled in November and submitted to vendors for proposals and quotations. In December several discussions were held with vendors concerning technical details of the cryogenics system. Subsequently a cryogenics system based on a design successfully used with previous GE IR vidicon systems was recommended.

A detailed investigation of video gating and signal processing techniques was delayed until November owing to a temporary manpower shortage. However, through a concentrated effort in November and December, this did not delay the overall program. After an analysis of video gating and level detection techniques, breadboard circuits were constructed to verify the recommended techniques. Laboratory demonstrations of these techniques, used in conjunction with an IR vidicon camera, were conducted for a representative of NASA-QRAL on 10 December 1964.

Requirements of the calibration source were investigated primarily in November. Attempts were made to determine a commercially available source which would be suitable without modification. This goal was achieved as described in section V. G of this report.

Activities near the end of the design study involved minor modifications in the configuration of the optical and cryogenics systems. Work on the Phase A report was pursued in December 1964 and January 1965.

C. Summary of Meetings

During the Phase A study a number of meetings were scheduled to review progress of the investigation and clarify technical details. Persons attending represented NASA-QRAL, Huntsville; GE Apollo Support Dept., Daytona Beach and Huntsville; and the GE Electronics Laboratory, Ithaca, N.Y. These meetings are listed below; a few of the topics discussed are also given:

Date/Location	Persons Attending	Topics
17 July 1964 Huntsville	R. W. Foster, NASA-QRAL M. C. Hollenbeck, GE-ASD	Clarification of Contract Requirements; System Configuration; optics for 1/8-in.-diameter microcircuits; operation with vacuum chamber
6 August 1964 Ithaca	R. Cedar-Brown, GE-ASD M. C. Hollenbeck, GE-ASD J. E. Harris, GE-E Lab	Review of Huntsville meeting - 17 July. Possible technical approaches.

Date/Location	Persons Attending	Topics
18 September 1964 Dayton Beach	R. W. Foster, NASA-QRAL E. Mitchell, NASA-QRAL R. Cedar-Brown, GE-ASD J. E. Harris, GE-E Lab	Review of system requirements; IR vidicon operation; cryogenics system; optical depth of field; visual viewfinder
10 December 1964 Ithaca	E. Mitchell, NASA-QRAL R. Cedar-Brown, GE-ASD K. Harper, GE-E Lab J. E. Harris, GE-E Lab H. Kump, GE-E Lab W. Teegarden, GE-E Lab W. Wernsing, GE-E Lab	Presentations by contributors to Study Program; IR vidicon performance; readout techniques; optical considerations. Demonstrations of IR vidicon and readout techniques
6 January 1965 Huntsville	R. W. Foster, NASA-QRAL E. Mitchell, NASA-QRAL J. Mitchell, NASA-QRAL J. Moore, NASA-QRAL E. Butts, GE-ASD R. Cedar-Brown, GE-ASD E. Slanker, GE-ASD J. Harris, GE-E Lab W. Teegarden, GE-E Lab	Review of Phase A Study and technical results; recommendations for IR system; expected performance; alternative approaches

IV. APPLICATION OF INFRARED TO ELECTRONIC CIRCUIT TESTING

A. Background Information

A number of articles have been published describing infrared techniques for testing electronic circuits and components. Some of these articles are listed in a bibliography at the end of Volume II of this report. These infrared techniques are based on the fact that current flowing in an electrical circuit will increase its temperature an amount ranging from a fraction of a degree to $100^{\circ}C$ or more, depending on the power dissipated and heat transfer conditions.

The amount of infrared radiation from a component, which is a function of its surface temperature and emissivity, can provide information about the operating conditions of the circuit in which the component is used. In many cases a circuit fault changes the current flowing through one or more components with a corresponding change in temperature and infrared radiation. The use of a suitable detector to determine the amount of infrared radiation from a specific component can also determine its operating conditions. If the detector is then moved in succession to measure radiation from each of the other circuit components, the condition of the entire circuit can be evaluated.

Infrared cameras have been developed which automatically scan the detector across a given field of view to produce an image of the IR radiation from the scene. However, an infrared camera utilizing a point detector has certain limitations. The typical point detector system consists of a single sensor located on the optical axis of the optics. Its angular resolution is defined by the dimensions of the detector and focal length of the optics. If it is to image, the entire optical system must be made to systematically scan the field of interest by a rather complicated mechanical arrangement. Since the mechanical scanning process is slow, this system will not respond to rapid thermal changes in the circuit being tested. The slow readout also increases the difficulty in adjustment and alignment of the camera. These difficulties are overcome with infrared imaging tubes which use an electron beam scanning process for much greater speed. A television camera using an infrared tube provides the capability of obtaining IR images of electronic circuits in real time.

B. Basic Considerations for IR Thermal Measurements

These investigations were conducted using guidelines either specifically established in Contract NAS 8-11715 or suggested in subsequent discussions with representatives of NASA-QRAL. One important factor which was considered was the expected temperature range of circuits and components to be measured. It was established that these temperatures might range from an ambient level as low as $60^{\circ}F$ ($\sim 288^{\circ}K$) to an upper level of $300^{\circ}F$ ($\sim 422^{\circ}K$). A circuit component operating at a given temperature emits infrared energy over a broad spectral band. Figure IV-1 shows the amount and spectral distribution of infrared radiation emitted by a blackbody source at various temperatures. The expected temperature range for elec-
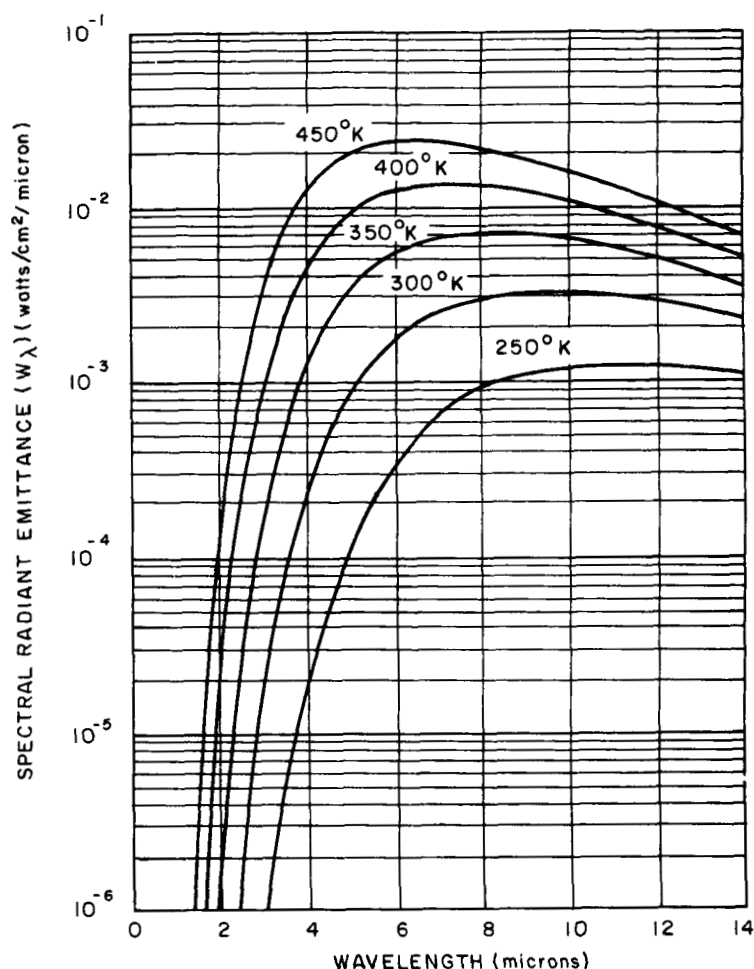
Figure IV-1. Spectral Distribution of Blackbody Radiation

tronic components would fall within this family of curves. These curves show that the amount of emitted radiation increases with the temperature of the source and at the same time the spectral distribution shifts toward the shorter wavelengths. It should be noted that the blackbody curves do not cross; therefore, in any spectral band the radiant emittance from a blackbody will always increase as its temperature increases.

One limitation of infrared circuit testing techniques is the ability of an infrared sensor to detect variations in IR radiation corresponding to small changes in component temperature. It was suggested by NASA-QRAL that the infrared measurements system should be capable of detecting temperature variations of 1°F (0.55°C) or lower for an ambient temperature of 60°F (~ 15°C). In this study program several factors which could limit the performance of the system were considered. Some of these are listed below.

1) Infrared image tube sensitivity: Image tube performance is discussed in Volume II of this report.

2) Optical efficiency: As described in section V. E, efforts were made to optimize performance of the IR optics by using high-speed optical designs with optical materials and coatings chosen for high transmission in the desired spectral region.

3) Signal processing: A subsequent section of this report discusses techniques such as signal integration which can be used to obtain maximum performance of the overall measurement system.

4) Atmospheric attenuation: Infrared radiation in certain spectral bands is absorbed by the presence of water vapor and other atmospheric gases between the source and the detector. Values of atmospheric attenuation for a five-foot path length were calculated. The resultant atmospheric transmission curve is plotted in Figure IV-2. The dips in the transmission curve are quite narrow except in the 5.5- to 7.5-micron band, and should have little effect on the performance of an IR system which operates outside this spectral region. For shorter path lengths atmospheric attenuation will be even less than indicated in Figure IV-2.

PATH LENGTH: 5 ft (1.52 M)
ALTITUDE: SEA LEVEL
RELATIVE HUMIDITY: 60.0 %
TEMPERATURE: 300.0 °K
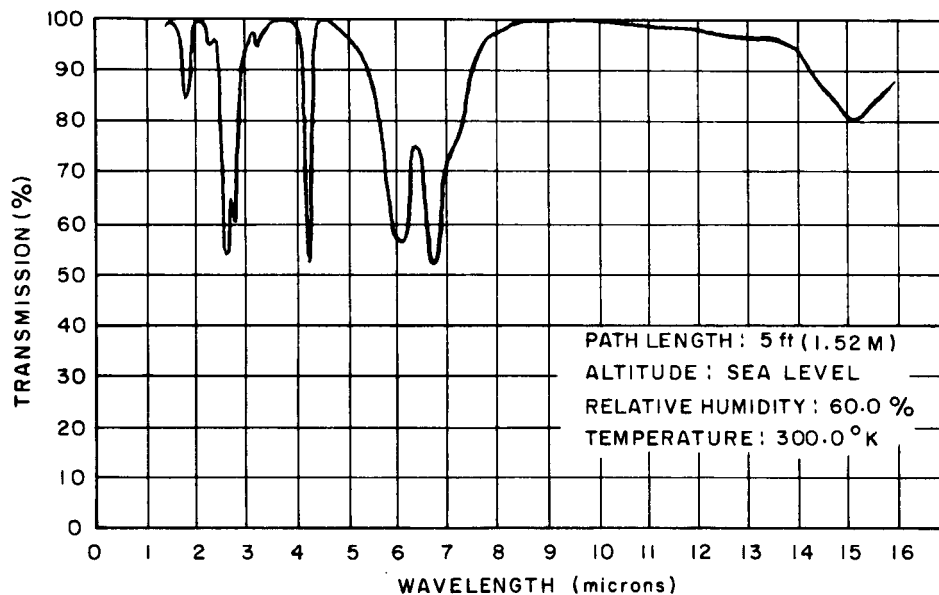
Figure IV-2. Atmospheric Transmission Corrected for H_2O Vapor, CO_2, and O_3

5) Surface emissivity: Infrared radiation from an object is not only a function of its temperature, but also its surface emissivity which may be any value between zero and unity. A dull, black surface has a high emissivity and will radiate more energy than a shiny surface at the same temperature. The spectral distribution curves of Figure IV-1 show the amount of radiant emittance for blackbody sources, that is, those with an emissivity of unity. Radiation from circuit components at a particular temperature can be expected to be less than indicated in Figure IV-1, depending on their surface emissivities.

Measuring the IR radiation from a component will allow its temperature to be determined only if the emissivity is also known. A method suggested to eliminate uncertainties due to unknown emissivities is to apply a uniform, high-emissivity

coating to all surfaces whose temperatures must be measured. Even though the coating has an emissivity less than unity, the same value will hold for all components and temperature measurements would be simplified. An ideal coating would be transparent in the visible spectrum so that component markings are visible; in the infrared spectrum the coating would have an emissivity of unity for maximum emittance and higher detectability with IR sensors.

V. SYSTEM DESCRIPTION

A. Functional Concept

A block diagram of the recommended system is shown in Figure V-1. With this system, a thermal image of the circuit being tested is focused on the retina of the IR vidicon, which is located in the camera head. The IR vidicon retina is scanned with an electron beam to develop a video signal corresponding to the thermal image. The video signal is amplified by a preamplifier circuit, also located in the camera head, and fed to the camera control unit. After further amplification and processing it is fed to the television monitor to generate a visible display of the thermal pattern being viewed.

The video signal from the preamplifier is also fed to the signal processor. This unit permits the operator to isolate and detect the signal corresponding to a specific portion of the scene for which a temperature measurement is desired. This is accomplished by means of an electronic gate generated by the signal processor. Controls for both gate position and gate size permit the operator to determine the temperature of specific portions of the scene. The position of the electronic gate is referenced to horizontal and vertical drive pulses generated by the camera control unit. These pulses are also available for synchronizing the monitor sweeps. The electronic gate signal is combined with the video signal fed to the monitor and provides the operator with a visual display of gate position and size.

The output of the signal processor is a dc voltage which is measured by a digital voltmeter to determine scene temperature. A permanent record of the voltmeter readings is provided by the printer shown in Figure V-1.

An infrared calibration source is required to permit calibration of the system for accurate temperature measurements. A temperature controller maintains the source temperature at the particular level desired for calibration purposes. The calibration procedure involves obtaining an image of the source and adjusting the signal processor calibration controls until the correct voltmeter reading is obtained.

The sensitivity of the IR vidicon can be adjusted by the operator to permit operation over a wider range of scene temperatures. The cyrogenics system shown in Figure V-1 is used to cool the IR vidicon to liquid-nitrogen temperature. Auxiliary power supplies for the signal processor circuits are also indicated in the block diagram. The various units which comprise this system are described in more detail in subsequent paragraphs.
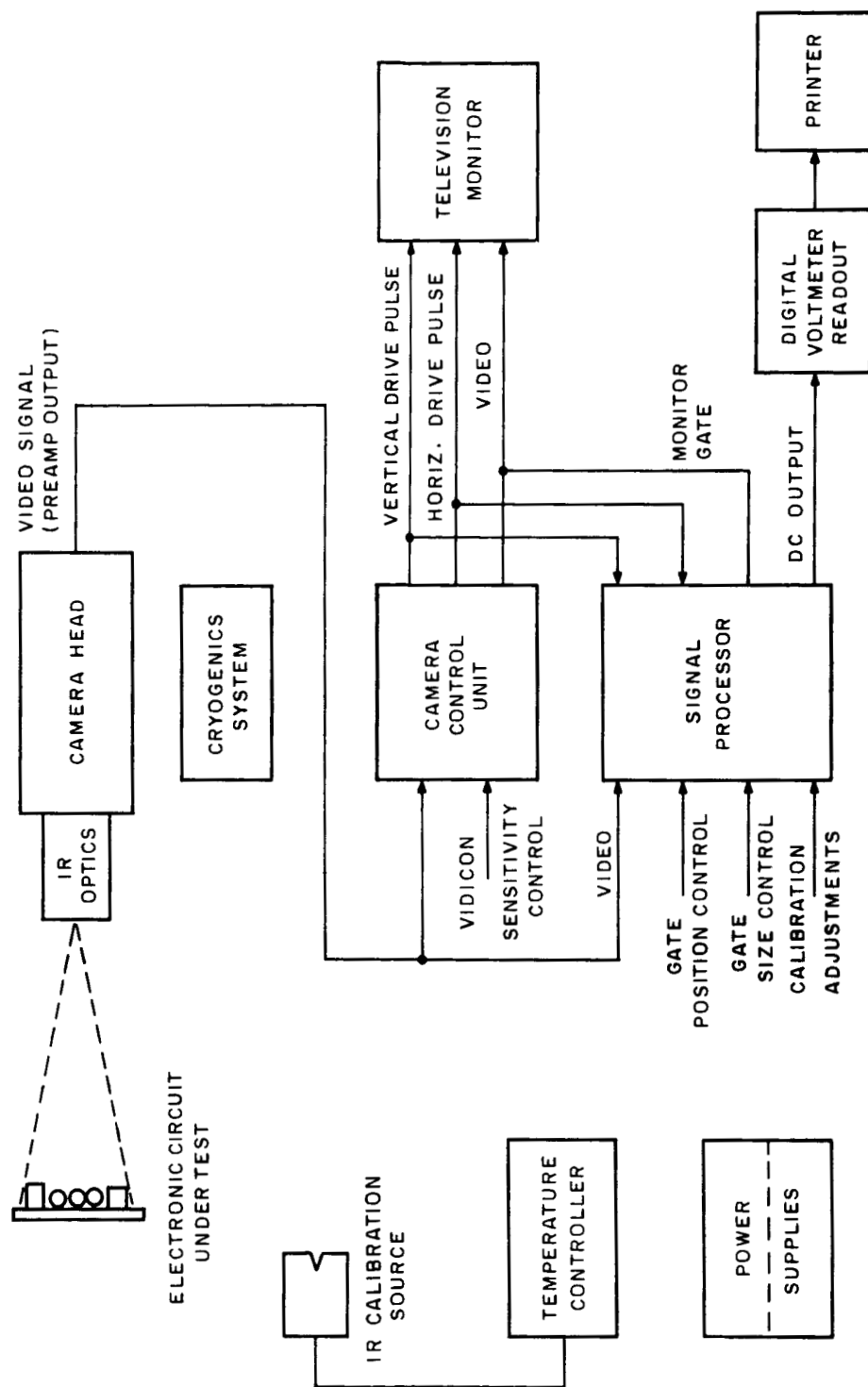
Figure V-1. Block Diagram of IR Vidicon System for Infrared Measurements

B. Mechanical Design Concept

The various components of the infrared measurement system will be mounted in three functional groups as shown in Figure V-2. The electronics rack is intended to be used by the operator as a station for controlling the overall system and measuring the thermal characteristics of the circuit being tested. The camera head assembly is positioned to view the test circuit and the IR calibration source is used for periodic system calibration. Twenty-five-foot cables interconnect the camera head assembly and calibration source with the electronics rack. To achieve the degree of mobility desired for laboratory operation, full swivel casters are specified for those major components whose weight exceeds 25 pounds. This applies to both the electronics rack and the camera head assembly.

The electronics rack shown in Figure V-3 includes the following components:

1) Temperature controller for IR calibration source

2) Digital voltmeter and printer

3) 17-inch television monitor

4) Operator's control panel

5) Pullout writing surface

6) IR vidicon control unit

7) Power supplies

8) Rack enclosure

9) Blower

The rack itself is an Emcor Model FR 126A, or equivalent, which is fully enclosed and mounted on four heavy-duty, full swivel casters. The casters have a combined load capacity of 800 lb. The total weight of the rack and the components mounted therein is approximately 600 lb, so that a 200-lb margin is available. The Emcor rack is equipped with a pullout writing surface (Model RS 22A) located 29-1/2 inches from the floor.

A blower (McLean No. 2EB512A, or equivalent) will be mounted from the rear of the rack, in the bottom position. Cooling air drawn in by the blower will be forced up through the cabinet and out through a vent at the top of the rear door. All components will be bolted directly to the rack with the exception of the camera control unit; it is mounted on pullout slide tracks for convenience when electronic alignment of the camera is required. When the control unit is pulled forward on the chassis slide tracks test points and adjustments located on the top of the unit are readily accessible. The operator then has a full view of the monitor as he proceeds with camera alignment adjustments.

The camera head assembly shown in Figure V-4 includes the following components:

1) Camera head

2) Cyrogenics system

CALIBRATION SOURCE

CAMERA HEAD ASSEMBLY
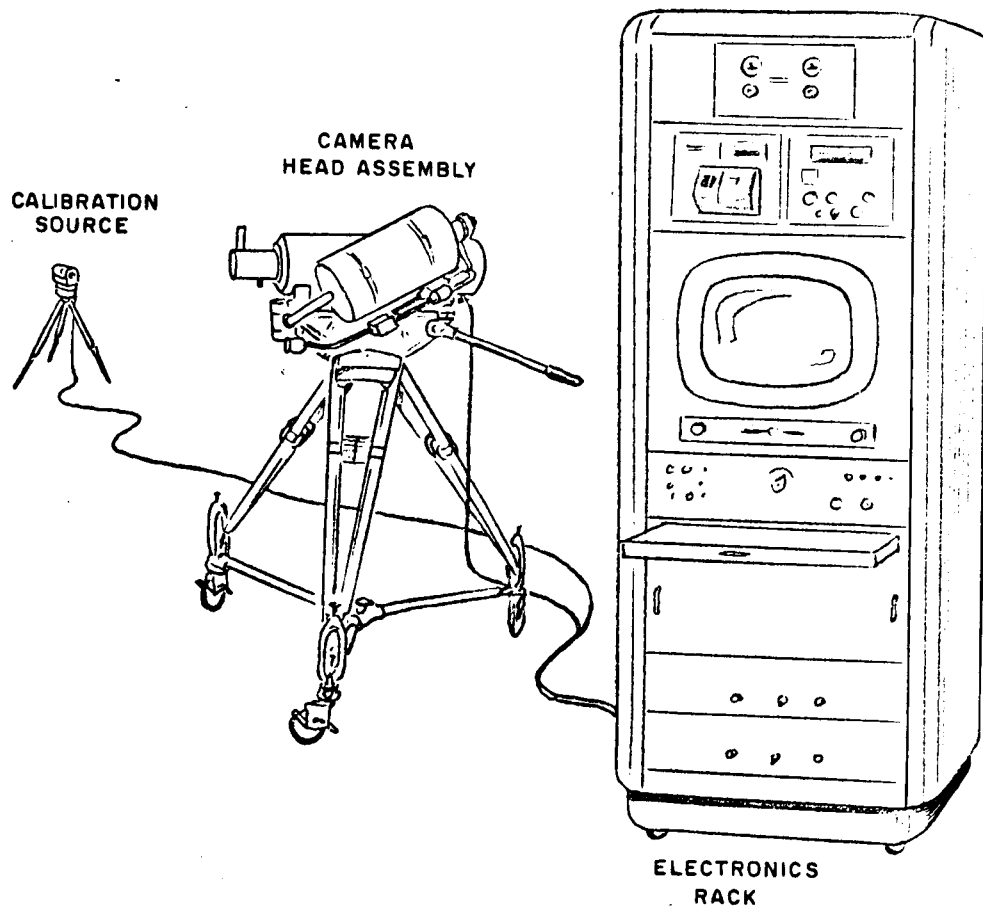
ELECTRONICS RACK

Figure V-2. IR Vidicon System for Infrared Measurements

REFLEX SIGHT

IR VIDICON CAMERA HEAD

IR LENS

CRYOGENICS
SUPPLY DEWAR

CRADLE TILT
HEAD

CELL
DEWAR

HEAVY DUTY
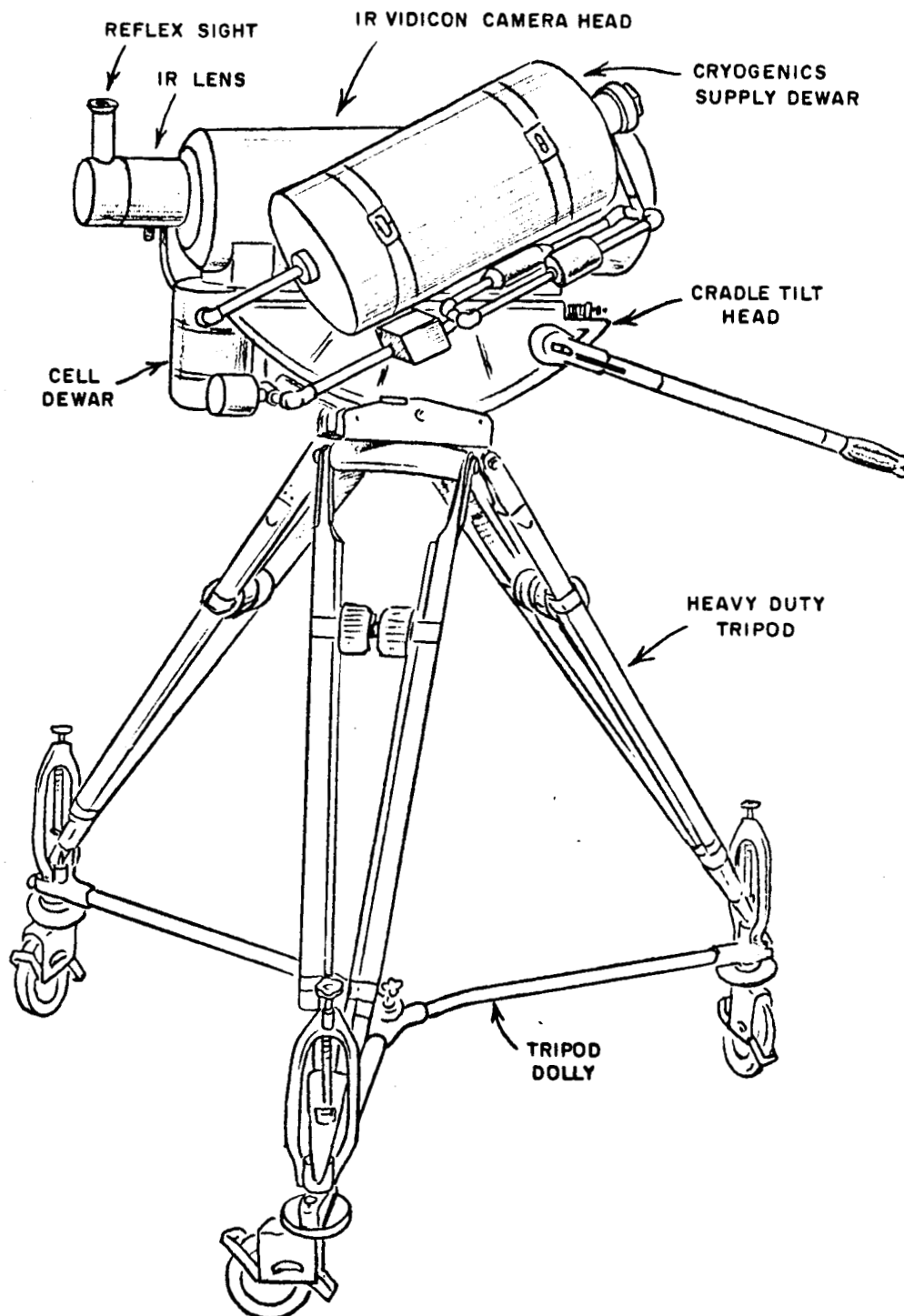TRIPOD

TRIPOD
DOLLY

Figure V-4. Camera Head Assembly for Infrared Measurements System
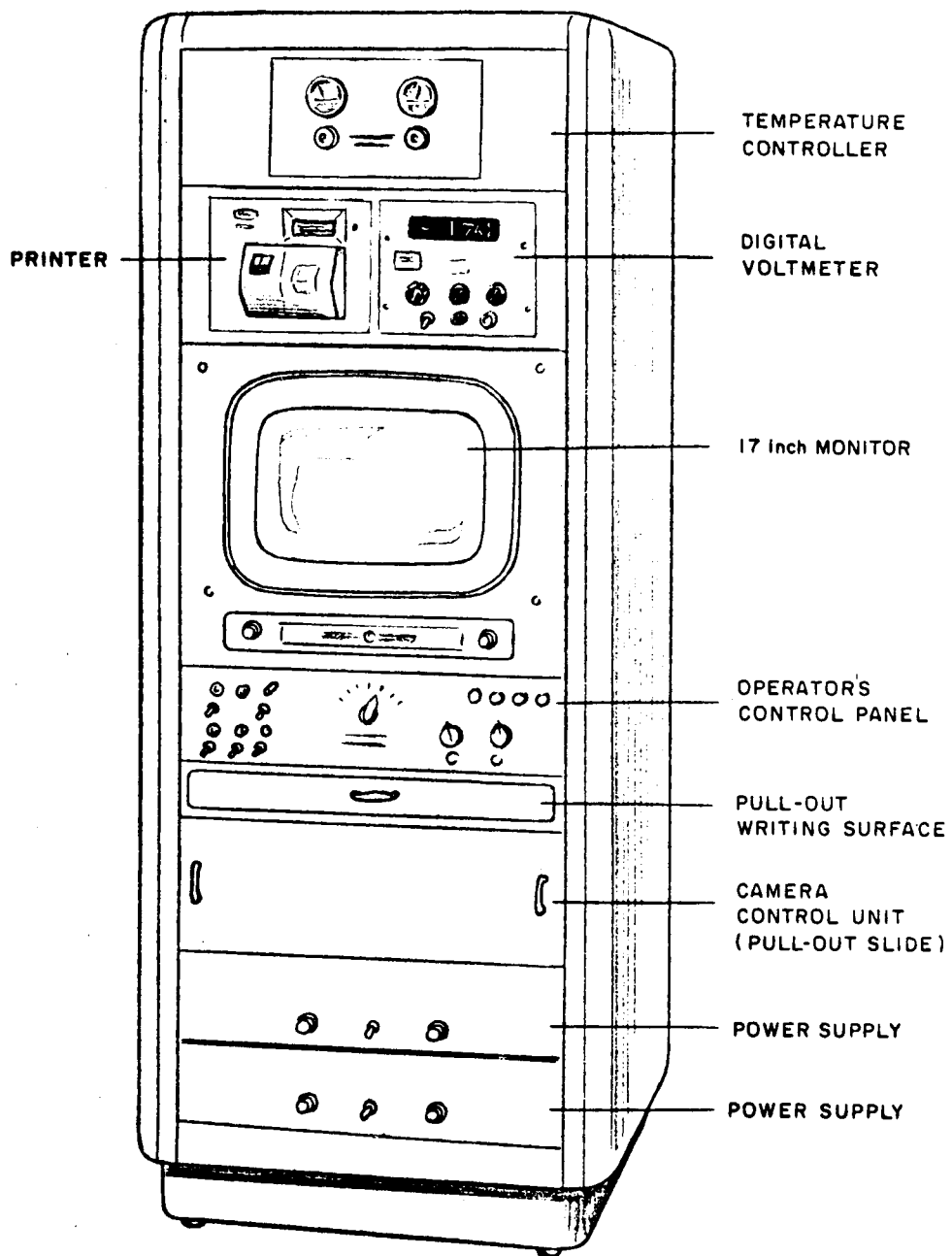
Figure V-3.   Electronics Rack for Infrared Measurements System

3) Optical assembly

4) Cradle tilt head

5) Heavy duty tripod

6) Tripod dolly

The cryogenics supply dewar is mounted directly to the camera head. This eliminates the necessity of using long, flexible, vacuum-insulated lines for transfer of liquid nitrogen to the cell dewar. The entire cryogenics system must move with the camera head as the cradle tilt head is moved through 360 degrees in azimuth and ±30 degrees in elevation; therefore, it should be reasonably compact and lightweight. Further cryogenics system requirements are discussed in a subsequent section of this report. Details of the camera head and the optical assembly are also described in other sections.

The cradle tilt head mounts on a heavy duty tripod which rests either directly on the floor or on a special tripod dolly as shown in Figure V-4. This dolly has three heavy-duty full swivel casters equipped with foot-operated wheel locks. The following components associated with the tripod assembly are recommended for this application:

Tripod: Camera Equipment Co., Model TR 3, or equivalent

Tripod dolly: Camera Equipment Co., Model D3, or equivalent

Cradle tilt head: Houston-Fearless, Model MCH-3, or equivalent

The infrared calibration source is mounted on a small, lightweight camera tripod as shown in Figure V-2. This unit and its tripod will be small and portable so that it can be readily positioned in the IR vidicon field of view during calibration.

Estimates of the weights of major components of the infrared measurements system are listed below.

Electronics rack: 600 lb

Camera head assembly (with tripod and dolly): 110 lb

Calibration source and tripod: 20 lb

Interconnecting cables: 11 lb

C. IR Vidicon Camera

1. General Description

The IR vidicon camera, when coupled to a TV monitor, provides the basic functions needed to obtain a visual display of the thermal patterns existing in a scene. The General Electric infrared television camera, Model UAR 252, is recommended for use with the infrared measurements system. When this camera is purchased, any electronic design or packaging improvements which have become available at that time should be reviewed; improvements appropriate to the requirements of the infrared measurements system should be included.

This camera uses the General Electric Type Z-7808 infrared vidicon tube to image radiation whose wavelengths extend well into the intermediate infrared region of the electromagnetic spectrum. This system, as shown in Figure V-5, includes two basic units, the camera head assembly and the control set, described separately below. The camera head contains the infrared vidicon tube and the related electrical components which, when properly energized, produce a video signal, or an electrical readout of the scene imaged on the vidicon target by the lens. The control unit provides electrical excitation for the elements in the camera head. It also provides amplification for the video signals from the camera head with processing required to produce a video signal compatible with standard monitors. The control unit can be remoted from the camera head by distances up to 25 feet.

The liquid-nitrogen cryogenic cooling required by the infrared vidicon tube can be supplied by either an open dewar mounted on the camera head, or by a special cryogenics system designed for a somewhat longer period of operation. A pressurized cryogenics system capable of operating for a two-hour period is recommended for this application. The camera system has been designed and constructed for use in military applications where small size, ruggedness, and maintainability are important. Nominal power requirements for the camera itself are 112 watts at 28 volts dc. The Z-7808 infrared vidicon is depicted in Figure V-6. Typical performance characteristics are included in Volume II of this report, classified confidential.

2. Camera Head

The camera head serves as a container and mount for the infrared vidicon tube, the focus, deflection, and alignment coils, the lens assembly, and the preamplifier. Its housing is a cylindrical aluminum container which is reinforced at three positions along its length to provide a basic structure for support of the component parts and a mounting base. Access to the interior of the camera head from the front may be gained by removing the lens mounting plate assembly. A removable cover permits access to the preamplifier and alignment coil which are located in the rear of the camera head. The front of the vidicon tube is supported by clamping the tube flange between Textolite rings. The socket end of the tube is held by a compressed O ring.

The low-level preamplifier is a magnetically shielded plug-in unit constructed around the vidicon tube socket to minimize lead lengths. Low-noise performance is obtained by using nuvistors in a cascode arrangement. A cathode follower output permits operation of the camera head assembly at a remote location from the camera control unit.

The electron multiplier voltage divider is located in the vidicon tube socket, which is a part of the preamplifier module. Three connectors--a coaxial connector for video signals, a high-voltage connector for anode and electron multiplier supply voltages, and a connector for the remaining power, sweep, and control voltages-- provide electrical interconnections between the camera head and the control unit.

The infrared vidicon camera head includes the following basic components or subassemblies:
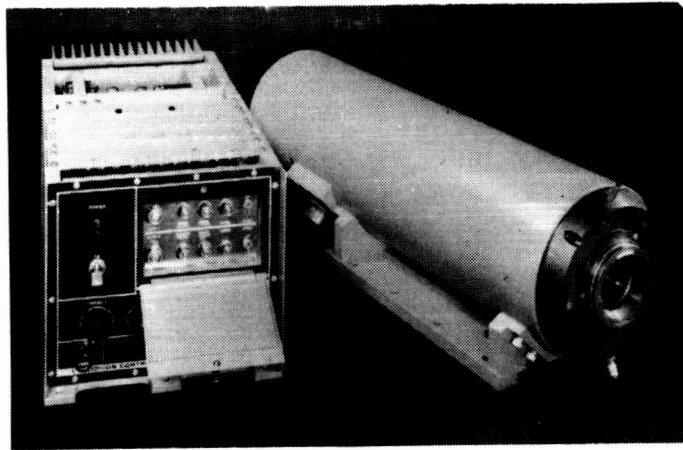
1) Z-7808 infrared vidicon tube

2) Preamplifier
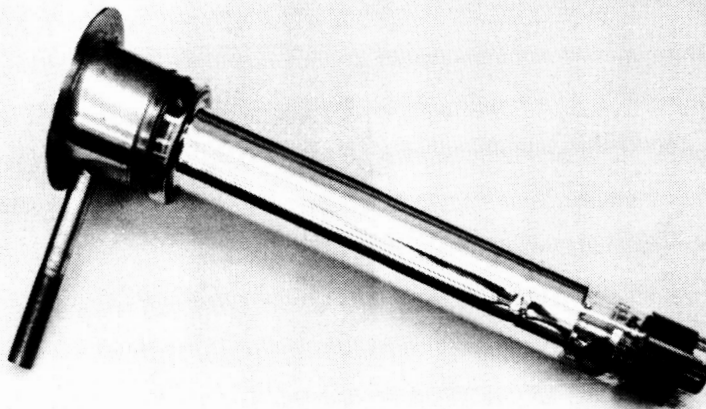
Figure V-5. Camera Head Assembly and Control Set

Figure V-6. Z-7808 Infrared Vidicon

3) Deflection coil

4) Alignment coil

5) Focus coil

6) Lens mounting plate assembly

Other parts associated with the camera head are available in a variety of configurations for diverse applications. These items are:

1) Cryogenic dewar with mounting bracket

2) Mounting base for camera head

3) Lens and optical filter assembly

3. Camera Control Set

The camera control set includes all of the electronic circuitry to supply the infrared vidicon camera head assembly with the appropriate operating voltages and currents, and to process the resulting video signal from the preamplifier. Solid-state circuitry is employed throughout. All dimensionally suitable components are mounted on welded-wire matrices, providing a type of construction which is inherently rugged, dimensionally stable and maintainable. Larger components are wired point-to-point and held in place by insulated standoffs. If the components have appreciable mass, auxiliary metal or nylon straps are used for additional support.

Circuits are constructed on modular metal cards to combine ruggedness with maintainability. The cards are guided into the control set housing by slots on two sides and by guide pins adjacent to the connectors on the bottom. A typical circuit card (with its mirror image) is shown in Figure V-7. If desired, any card can be removed and desk-top maintenance checks performed with power on by using a cheater card with its extension cable. The power supply and drive circuitry are thermally connected to the chassis and cooled by radiation and free convection. Primary operator controls are located on the front panel. Secondary control functions, such as focus and alignment adjustments, are located behind a hinged cover on the control panel.

Input power requirements are 112 watts at 28 volts dc ±10 percent. A series diode is used for protection against reversed input voltage. The input power circuit includes a fuse located on the front panel.

The modules or subassemblies in the camera control set and the function of each are as follows:

1) Control Panel - Provides controls and switches for camera operation and adjustment.

2) Video Amplifier - Provides wideband amplification for video signals from the preamplifier. Blanking and sync pulses are also generated and added to produce a composite video signal compatible with standard monitors.

3) Synchronizing Generator - Produces pulses at the vertical rate of 60 cps and the horizontal rate of 15. 75 kc for operation of various camera circuits.
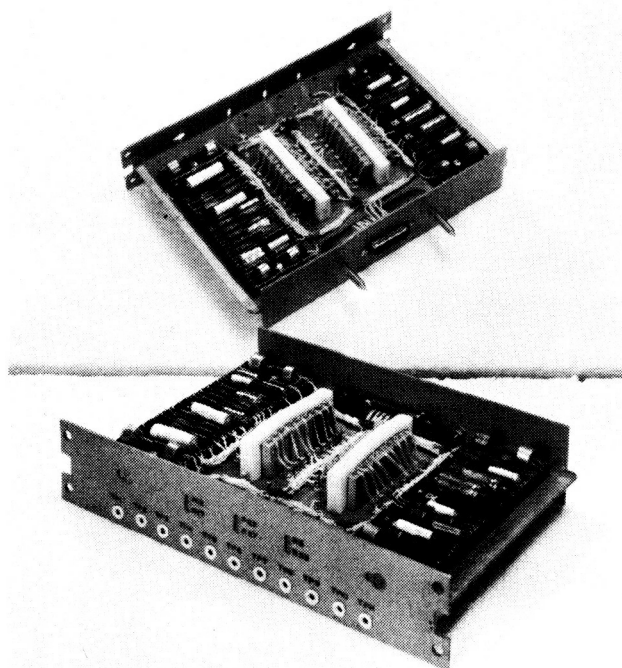
Figure V-7. Typical Circuit Card with Mirror Image

4) Vertical Deflection - Produces a trapezoidal sweep voltage for the vertical deflection coils. Combines horizontal and vertical pulses for blanking the vidicon target in a circuit which also provides sweep failure protection. Includes a focus current regulator circuit.

5) Horizontal Deflection - Produces a sawtooth sweep current for horizontal deflection coils and horizontal blanking pulses for the generation of the composite video signal in video amplifier.

6) Power Supply - From a 28 v dc input, this unit produces all regulated voltages for operation of the entire camera. Four power transistors associated with the power supply regulators are located on the back panel.

7) Back Panel - Includes connectors, reverse voltage protection diode, regulator transistors, and heat radiator.

4. Specifications for Model UAR-252 Infrared TV Camera

    a.   Image tube: General Electric type Z-7808 infrared vidicon

    b.   Camera head dimensions

        (1) Length (less optics): 19.3 inches

        (2) Diameter (housing): 6 inches

        (3) Projection of cold finger beyond housing: 3.5 inches

    c.   Camera head weight (less optics and cryogenics dewar): 31.5 lb

    d.   Control unit dimensions: 8 in. wide × 7.19 in. high × 17.5 in. deep

e.   Control unit weight: 25 lb

f.   Special control unit features

   (1) Completely transistorized

   (2) Plug-in circuit cards with welded-wire matrix modules

   (3) Removable control panel for remote operation

g.   Power requirements: 112 watts nominal at 28 v dc ±10 percent

h.   Video output signal: 1 volt composite video, 75 ohm source impedance

i.   Auxiliary sync outputs

   (1) Vertical: 5 v pulse, 1.1 msec wide

   (2) Horizontal: 7.5 v pulse, 5 μsec wide

j.   Sweeps:

   (1) Type: electromagnetic

   (2) Frame rate: 30 cps

   (3) Field rate: 60 cps

   (4) Scan: 525 lines interlaced 2:1

D.   Video Processing and Display

1.   Statement of Problem

It has been proposed that the video output from an infrared vidicon focused on an electrical circuit under test could be processed to provide a direct presentation of the temperature of any particular component in that circuit. This portion of the investigation was performed to determine the feasibility and the most practical approach to utilize a video signal for such a purpose.

The operating conditions assumed for this analysis are as follows:

Video Signal: 1 volt peak-to-peak composite from a 75-ohm source.

Data Rate: 30 frames per second with a 2:1 interlace.

Image Size: minimum size to be interrogated is 0.02 $\times$ 0.02 in. on a
             1 in. retina (raster size is 0.6 in. high $\times$ 0.8 in. wide on
             retina)

Temperature Range: measurements confined to range from 16°C to
                    150°C (approx. 61°F to 302°F).

Ambient Temperature: 15.5°C minimum (approx. 60°F)

Video Signal-to-Noise Ratio: minimum of 1:1 at low temperatures
                              (peak signal/rms noise)

Dynamic Range: 60:1

2. Proposed Solution

The general form of the proposed solution is shown in Figure V-8. The video input can pass through the gate only when the scanning beam passes through a preselected area which is to be interrogated. The output from the gate is then in the form of groups of pulses occurring at a 60-cps repetition rate. The amplitudes of these pulses are averaged and stored in the level detector. This level is operated on in the level-temperature converter to yield a voltage output proportional to the average temperature of the portion of the scene under interrogation. A digital voltmeter and printing recorder form a display and permanent record combining both high accuracy and high dynamic range.

A second output from the gating circuit is connected to a cursor generator and finally mixed with the incoming video to provide a signal to a monitor which indicates the portion of the scene whose average temperature is being measured. A more detailed description of the considerations given to the major blocks is found in the sections that follow.
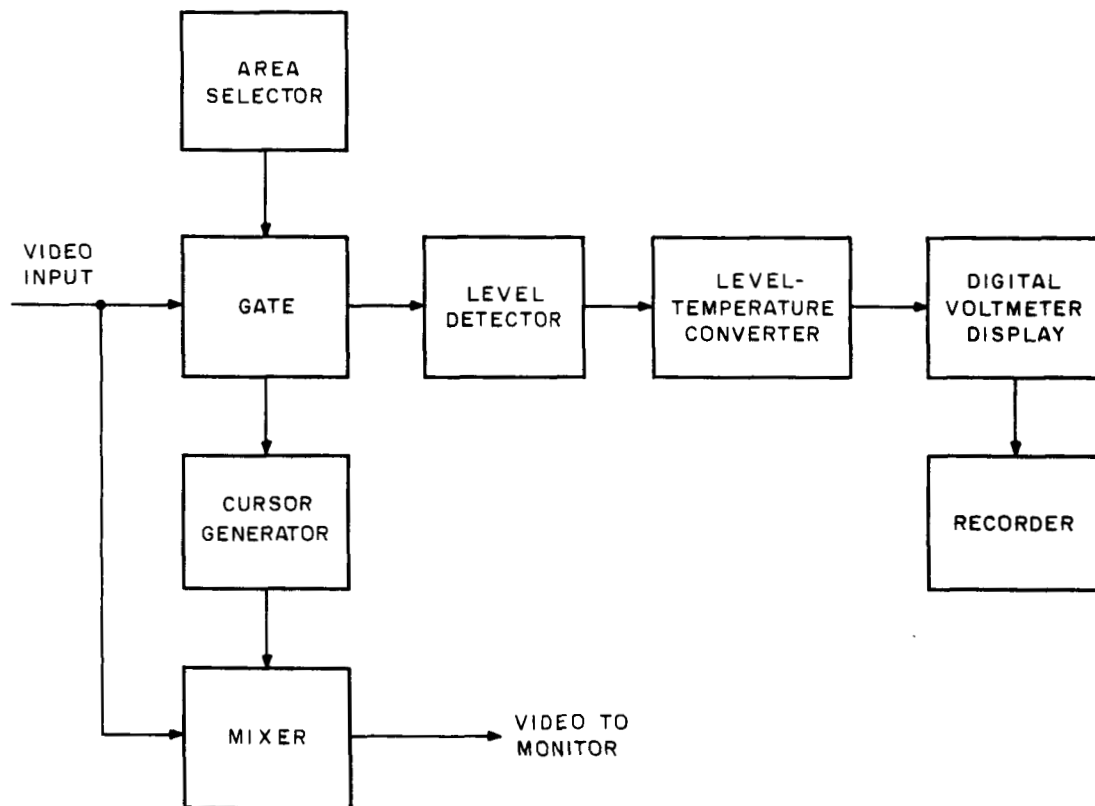

Figure V-8. Block Diagram of Proposed Solution

3. Gating Techniques

Two approaches for obtaining the video "on" gating signal were considered. One method utilizes a light sensor in a "pencil" that is held up to the face of the monitor. When the scanning beam passes in front of the sensor, an output is obtained which is time-coincident with the video in that portion of the scene. This output can operate the video gate shown in Figure V-8. A second all-electronic technique generates a video gate using the horizontal and vertical sync signals as a time reference. These sync signals are delayed and used to trigger monostable multivibrators which provide gating pedestals. An AND gate driven by these outputs allows the video to pass through only when the pedestals are coincident and a particular rectangle is selected for interrogation.

In comparing the two techniques the following limitations of the pencil technique were noted:

1) The phosphor decay time of the monitor would preclude obtaining a usable gate turnoff directly.

2) The gating signal would have to undergo amplification and then clipping to assure an adequate signal under low monitor brightness conditions.

3) A means for focusing the image on the light sensor is required and must allow for a varying image size.

4) The "pencil" must be held in position. Any jitter causing the pencil to move partly or intermittently out of the measurement area may cause large and detrimental amplitude excursions.

5) A long-term measurement of a particular component is not feasible.

6) Occlusion of the image by the pencil increases the difficulty in obtaining accurate and repeatable position settings.

The all-electronic technique has two additional advantages in operational flexibility. These are:

1) A remotely located monitor can be used if desired.

2) Several cursors and measurement systems can be used simultaneously to investigate and compare many components at the same time or to measure temperature differences directly.

The electronically generated gating system requires more circuitry and it takes a few seconds longer to position the gated area, but it is felt that these are of considerably less consequence than the above difficulties, and the electronic system is therefore recommended. A block diagram of the recommended gating system is shown in Figure V-9.

Horizontal and vertical sync signals are fed to monostable (one-shot) multivibrators to obtain a variable delay. The outputs are fed to second one-shot multivibrators to set the desired width or height of the area to be measured. Potentially,
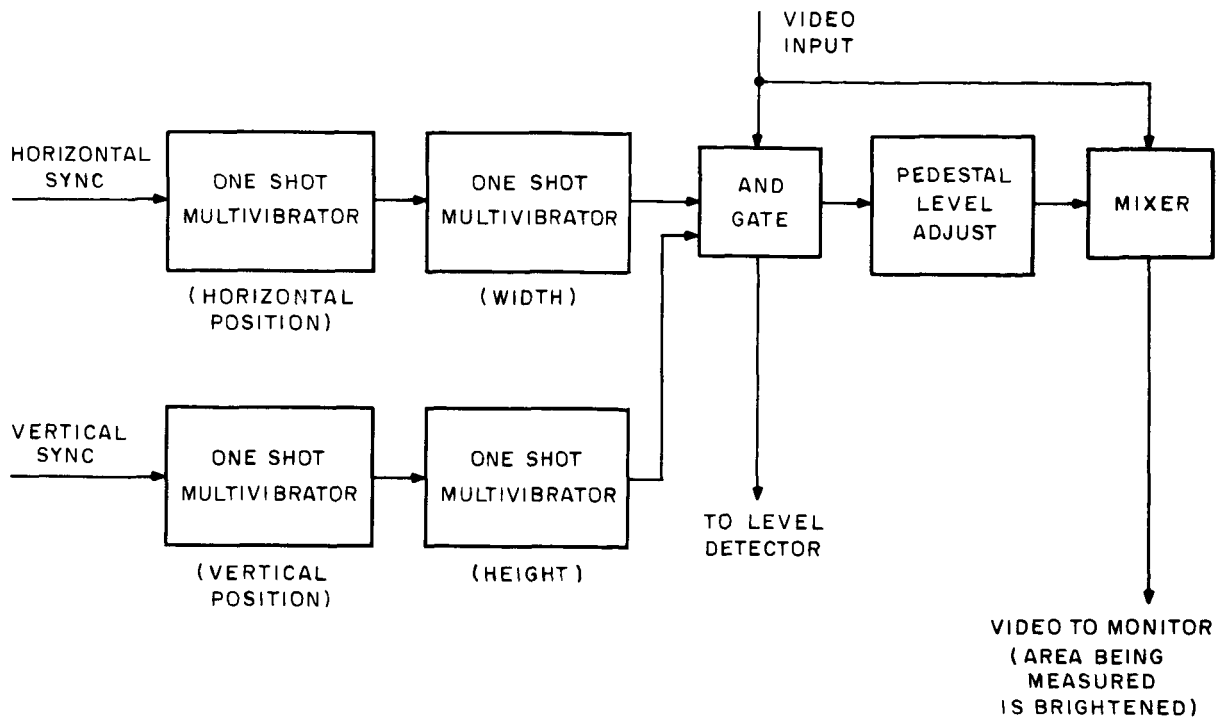
Figure V-9. Gating System Block Diagram

a horizontal and a vertical bar have now been generated. The AND gate passes video only in the common area. The output from the gate, which is in the form of a pedestal, is also operated on and mixed with the video to provide the monitor with a brightened rectangle indicating the area under measurement. This brightening is adjustable and does not cause the video to saturate but allows the component to be seen through it.

4.   Video Level Detector

The video signal from the gate in Figure V-8 will be in the form of a burst of pulses recurring at 16. 7-millisecond intervals. The worst condition from an information standpoint will be when the interrogated area is at a minimum. Considering this to be the case, the area will be 0. 02 in. wide by 0. 02 in. high on a 1 in. retina. The horizontal scan takes 63. 5 μsec per line total with an 8 μsec flyback. With a raster width of 0. 8 in. , the time to scan the width of the interrogated area is

$$\frac{55.\,5 \times 0.\,02}{0.\,8}\; \mu\text{sec} = 1.\,4 \times 10^{-6} \text{ sec}$$

The vertical scan takes 16. 7 msec per field total with a 1. 1 msec flyback time. The raster will be 0. 6 in. high and the time to scan the height of the interrogated area will be

$$\frac{15.\,6 \times 0.\,02}{0.\,6}\; \text{msec} = 520 \times 10^{-6} \text{ sec}$$

This corresponds to approximately 8-1/2 lines of a field or about 17 lines on an interlaced frame as illustrated in Figure V-10.
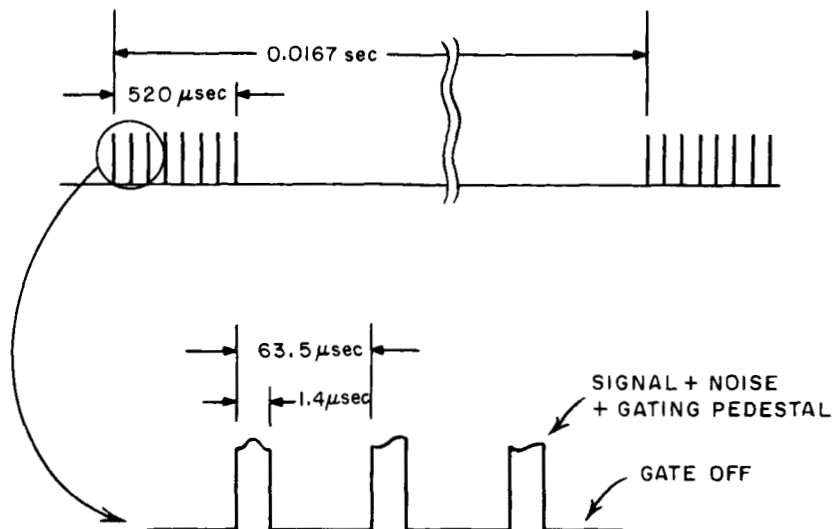
Figure V-10.   Gated Video

To determine the necessary averaging time to process data of this form the following relationship was used

$$(\sqrt{I}) \, (\epsilon) \left(\frac{S}{N}\right) = K_\gamma$$

where

I = number of independent samples
(note: this is equivalent, not to the number of pulses, but rather equivalent to the total sampling time multiplied by the noise bandwidth.)

ϵ = the normalized error limit

S = signal amplitude (peak-to-peak)

N = noise amplitude (rms)

K_γ = number of standard deviations for a confidence level of γ

For the example being considered, these constants will be as follows:

ϵ = 0.01 (i.e., one-percent error)

$\frac{S}{N}$ = 1

K_γ = 1.65 (this yields a confidence of 90 percent that the one percent error will not be exceeded)

Noise bandwidth = 5 Mc

Sampling time per pulse = 1.4×10^{-6} sec

V-16

Solving the equation for I, we have

$$I = \left(\frac{K_\gamma}{\epsilon \times \frac{S}{N}}\right)^2 = \left(\frac{1.65}{0.01 \times 1}\right)^2 \cong 27,200$$

The number of independent samples per pulse is $5 \times 10^6 \times 1.4 \times 10^{-6} = 7$. It will therefore be necessary to average $27,200/7 \cong 3900$ pulses. At a rate of 8 pulses per field and 60 fields per second, the time required will be $3900/8 \times 60 \cong 8$ seconds.

Figure V-11 shows the tradeoff between averaging time and the uncertainty due to noise. Two families of curves are plotted: one for a S/N of 1 and one for a S/N of 3. Each represents a variety of confidence levels. These are worst-case plots and any increase in the interrogated area decreases the averaging time directly. For example, increasing the interrogated area to 0.04×0.04 in. would reduce the averaging time by a factor of 4, keeping all other factors constant. An averaging time of from 5 to 10 seconds seems reasonable to assume. The required accuracies will dictate a maximum allowable measurement error of about one percent.
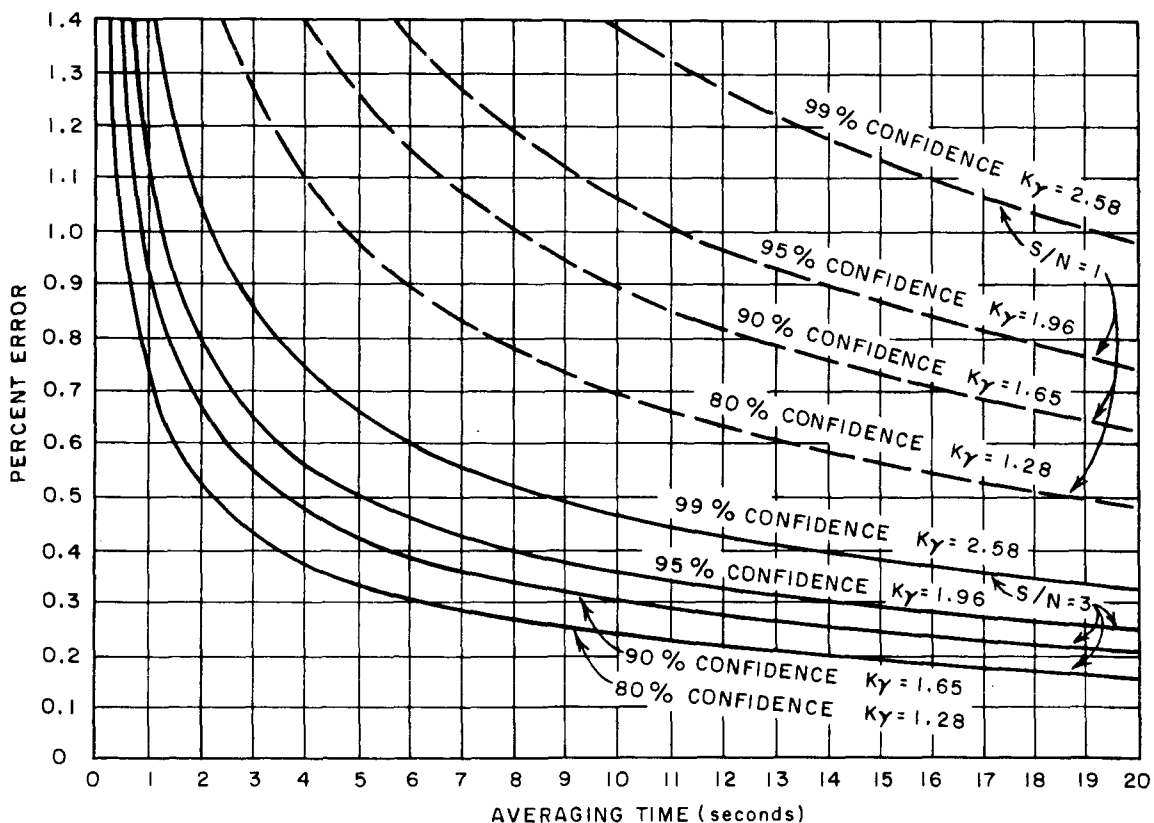
Figure V-11. Integration vs Percent Error

The actual processing of the pulses requires that the averaging not include the gated off time. The average value must represent the average "on" level only. If an overall average were used, the output level would be sensitive to the pulse width and the number of pulses sampled per unit time. At the other extreme, peak detection would not be sensitive to pulse width or number, but would include an error related to noise peaks.

Figure V-12 shows two suitable averaging circuits in ideal form. In practice, a transistor driven into saturation by the input pulses would replace the synchro-

A.

B.

Figure V-12. Ideal Averaging Circuits

nous switch. The charging time constant, which is approximately R_1C_1 (for $R_2/\beta \ll R_1$), must be set to average the desired amount of information. In the previous example, a real time of 8 seconds was needed for averaging; however, R_1C_1 should be set at $I/BW \cong 27,200/5 \times 10^6 \cong 5.4 \times 10^{-3}$ sec. This would be the averaging time constant for a continuous signal; the synchronous switch causes equivalent charging conditions on a piecewise basis. With a higher S/N, improved readout accuracy would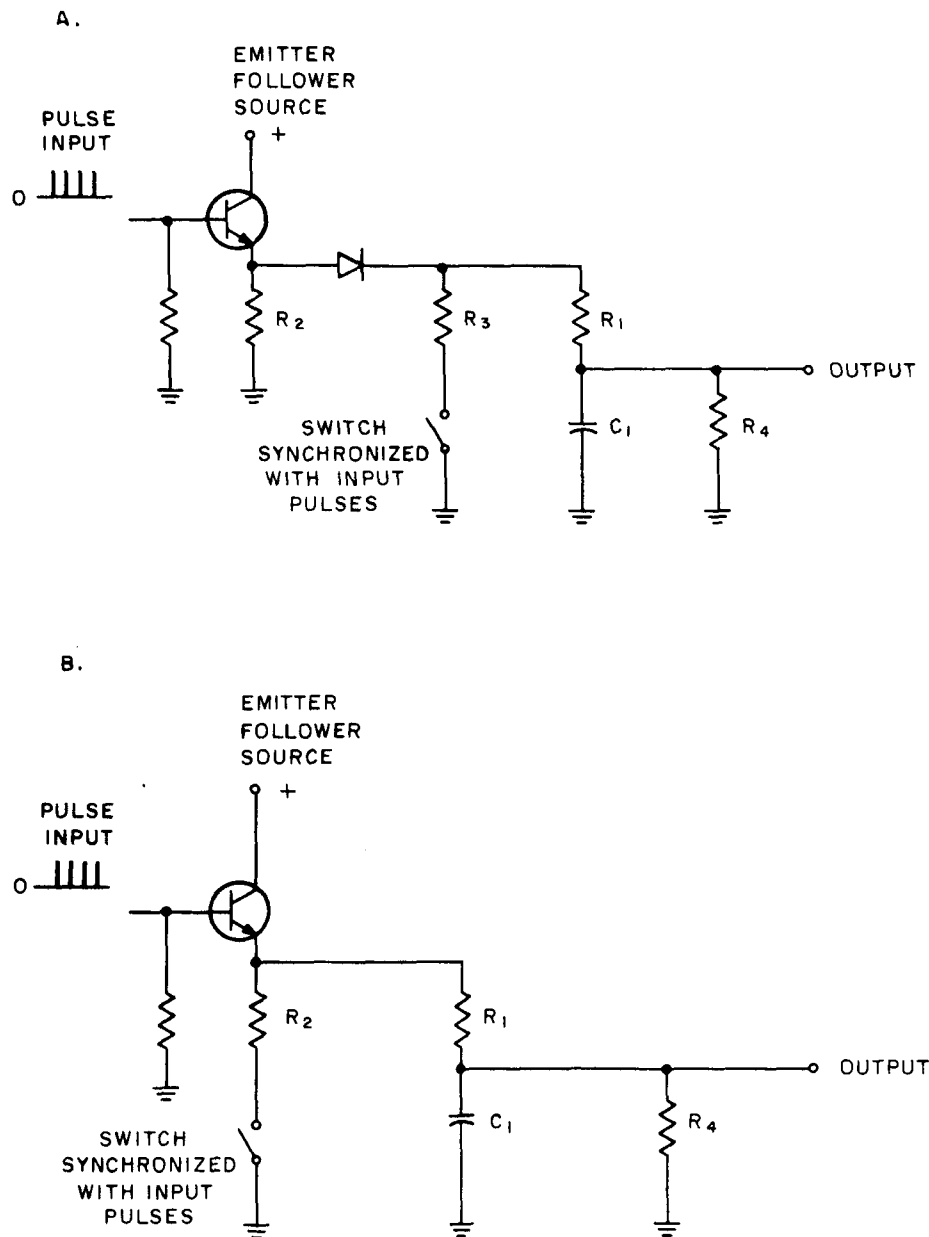 be obtained if the averaging time was not changed. If the original accuracy is satisfactory, an alternative would be to decrease time time constant R_1C_1 and shorten the averaging time for a more rapid readout. This would be the averaging time constant used if the signal were continuous; the synchronous switch causes the charging characteristics to be piecewise equivalent to that.

The output loading represented by R_4 should be such that in the real averaging time (8 seconds in the example) the decay is held to less than the tolerable error (one percent in the example). If the decay becomes greater than this, pulse width variations will be able to cause more error than this percent in the extreme cases. The criterion is then

$$e^{-\frac{8}{\tau}} = 1 - 0.01$$

$$\frac{8}{\tau} \cong 0.01$$

$$\tau = R_4C_1 \cong 800 \text{ seconds}$$

5. Level-Temperature Converter

Once a representative average of the gated video has been established, this voltage must be converted to the proper temperature indication. Two identifiable transfer characteristics must be synthesized, both of which are associated with the IR vidicon response.* First, the equivalent sensor irradiance of the vidicon depends on the interplay of blackbody radiation, the tube spectral response, and optical transmission as a function of wavelength. The net result is empirical and shows a pronounced sensitivity to higher temperature radiation. The second function relates the output signal to the equivalent sensor irradiance and is an expressable function of the form

$$A = CH^\gamma$$

where

A = output signal amplitude

C = constant

H = sensor irradiance

γ = constant

---

* For details of the response characteristics of an IR vidicon, see Volume II of this report.

The level-temperature converter operates on the output level from the vidicon to provide a voltage linearly proportional to the absolute temperature of the portion of the scene being interrogated.

Methods of generating this overall empirical transfer characteristic to the necessary accuracy have been investigated. A graphical method of solution is possible and, though it does not have the desirable automatic features of electronic means, it could provide the information with relative simplicity and less expensively. (Refer to Figure V-13 which illustrates this technique.) A graph pertaining to the particular
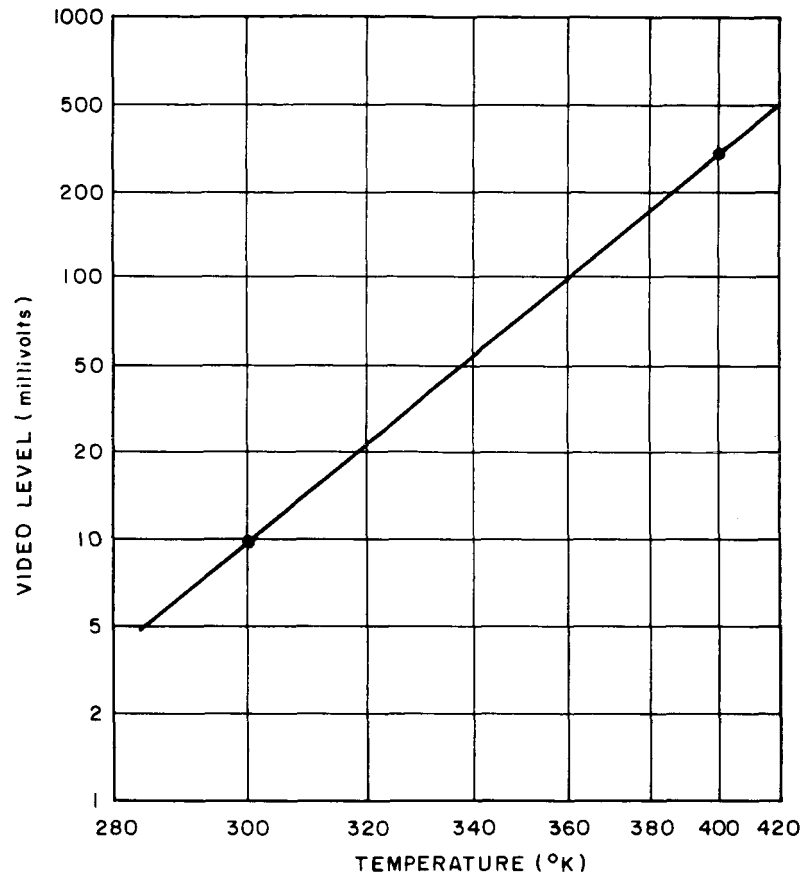
Figure V-13. Graphical Level-Temperature Converter

vidicon in use would be supplied as shown. It would have the appropriate nonlinear temperature scale reflecting its own anomalies. To calibrate, a low temperature source (300°K in this example) is interrogated and a point is marked on the graph at the output voltage level read. Then a high-temperature source (400°K in this example) is interrogated and the output voltage applying to it is also recorded. A straight line connecting these points will then represent the proper calibration for the conditions in use. If the system adjustments are changed, a new line will be necessary, but each condition could be represented by some easily found straight line. A pad of calibration blanks could be supplied or the proper nonlinear temperature scale could be easily determined in the field with only a blackbody whose temperature can be varied.

An electronic solution for the level-temperature converter necessitates either the synthesis of a nonlinear amplifier whose characteristics can be matched to empirical data or some technique of video comparison. Video comparison methods require many reference blackbodies (which could be synthesized using a single blackbody and a set of special filters) or some means of measuring radiation spectral characteristics. A brief survey of comparison techniques indicated that the nonlinear amplifier approach should be considered first, considering the required system accuracy.

The empirical response characteristics relating equivalent sensor irradiance to temperature were analyzed first. Figure V-14 shows a typical response characteristic which takes into account both the response of a vidicon and optical transmission as a function of wavelength. The first attempt to match this curve assumed a solution of the form $H = CT^n$. The best fit displayed an error of about $3^\circ C$, which was not close enough. The next attempt assumed a solution of the form $H = CT^n + K$ and was analyzed on a digital computer. The resultant curve, plotted in Figure V-14 shows a
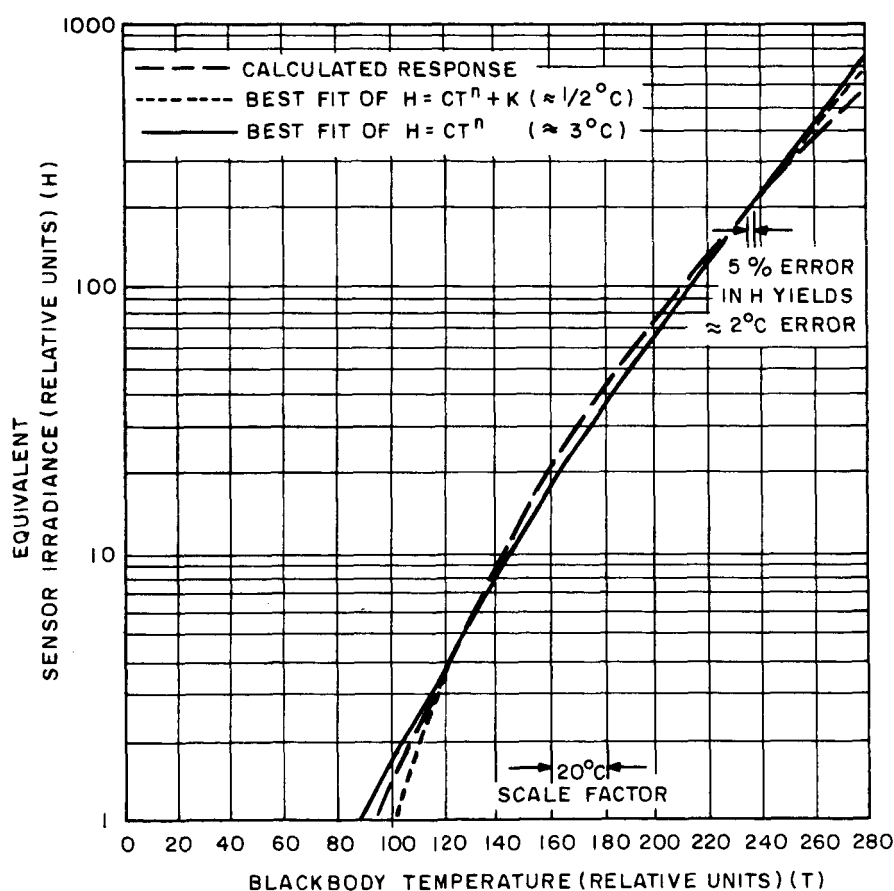
Figure V-14. Typical Response Characteristics for Vidicon,
Optics, and Blackbody

fit to no worse than $1/2^\circ C$. From a measurement on the plot of the vidicon sensitivity characteristics on that graph, it can be seen that a 5 percent error in the measured irradiance represents about a $2^\circ C$ error. If a maximum error of $1^\circ F$ ($0.56^\circ C$) is desired the system accuracy should be held to about 1-1/2 percent and the contribution of $1/2^\circ C$ from curve fitting is quite tolerable.

The overall function relating A to T, which is to be simulated, is then

$$A = C_1 H^\gamma$$

where

$$H = C_2 T^n + K$$

In these expressions C_1 and γ are determined by system adjustments and C_2, n, and K are associated with the particular vidicon in use. Combining these,

$$\left(\frac{A}{C}\right)^{1/\gamma} = C_2 T^n + K$$

which is of the form

$$T = (C_3 A^\alpha + C_4)^\beta$$

where C_3 and α will vary with system adjustments and C_4 and β will be a function of the vidicon.

A further attempt was made to find an approximation to this overall expression which would be accurate enough and yet simpler to implement. If, in one case, the T vs H curve is assumed to be a parabola about the linear axis on a log-linear plot, we may say that

$$T = T_0 + C_5 (\log H - \log H_0)^2$$

and therefore

$$\log H = \log H_0 + \sqrt{\frac{T - T_0}{C_5}}$$

If, in a second case, the axis of the parabola were turned 90 degrees so as to be along the log axis the form would be

$$\log H = \log H_0 + C_6 (T - T_0)^2$$

The A vs H curve is assumed to be a straight line on a log-log plot and

$$\log A = \gamma \log H + C_7$$

Substituting for log H, the combined expression then becomes:

$$\log A = [\gamma \log H_0 + C_7] + \gamma \sqrt{\frac{T - T_0}{C_5}} \quad \text{for the first case,}$$

$$\log A = [\gamma \log H_0 + C_7] + \gamma C_6 (T - T_0)^2 \quad \text{for the second case.}$$

The first case is easier to simulate since it will involve a squaring operation rather than taking a square root to get T from A. The assumed form is then

$$\log A = C_8 + C_9 \sqrt{T - T_o}$$

Constants for this expression were approximated by hand using a trial-and-error method; the crude results are plotted in Figure V-15. Additional trials with new constants would provide a closer match and greater accuracy at low temperatures, where the curve has its shallowest slope. This would be desirable even at the ex-
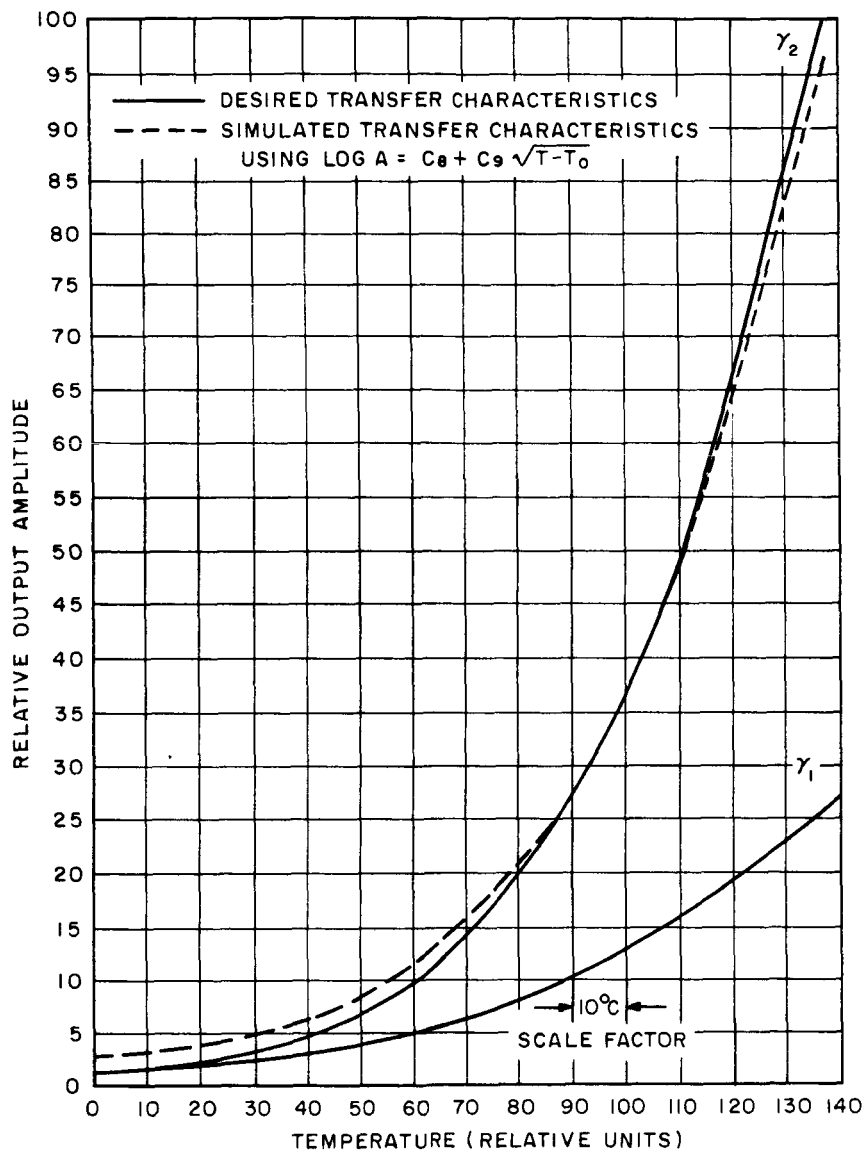

Figure V-15. Curve Fitting of Overall Transfer Characteristics

pense of a poorer fit at higher temperature in order to minimize temperature error under worst-case conditions. This expression appears to be the best approximation yet derived when all factors are considered. If, upon further investigation, this is not satisfactory, a diode curve-matching technique can always be employed, but that necessity appears unlikely.

A block diagram of the proposed level-temperature converter is shown in Figure V-16. For the log amplifier, an approximation could be made using the logarithmic forward conduction characteristics of a diode or using several diodes in a piecewise linear approximation. Other possibilities include using operational amplifiers or obtaining a commercially available log amplifier which offers sufficient accuracy.
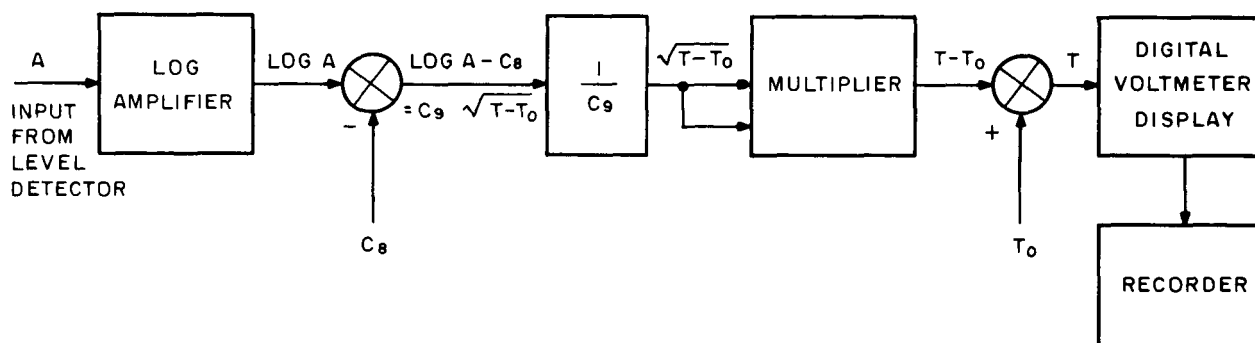
Figure V-16.   Proposed Level-Temperature Converter

6.   Experimental Investigations

To demonstrate the feasibility of the gating technique and level-detector described in paragraphs 3 and 4, two laboratory experimental models were built and tested. For these tests, line selector oscilloscopes (such as the Tektronix 545) were employed as gate generators. A horizontal sync signal from the camera chain was fed to the TRIGGER OR EXTERNAL SWEEP IN connection on the scope. The horizontal display was switched to DELAYING SWEEP, and a delayed pulse of adjustable width and delay time was obtained from the + GATE MAIN SWEEP output. The delay time was referenced to the horizontal sync signal in this way. In a similar manner, a second scope was employed to generate a delayed vertical sync pulse. These are the + GATE inputs referred to in Figure V-17 which shows a block diagram of Model I of the video gating and level detector.

Figure V-17.   Block Diagram of Video Gating and Level-
Detector Circuit for Model I

In this circuit the video is allowed to pass through the emitter follower only when the horizontal and vertical plus gates occur coincidently. The output from the emitter follower contains a dc gating pedestal and the video. The video riding on this pedestal is ess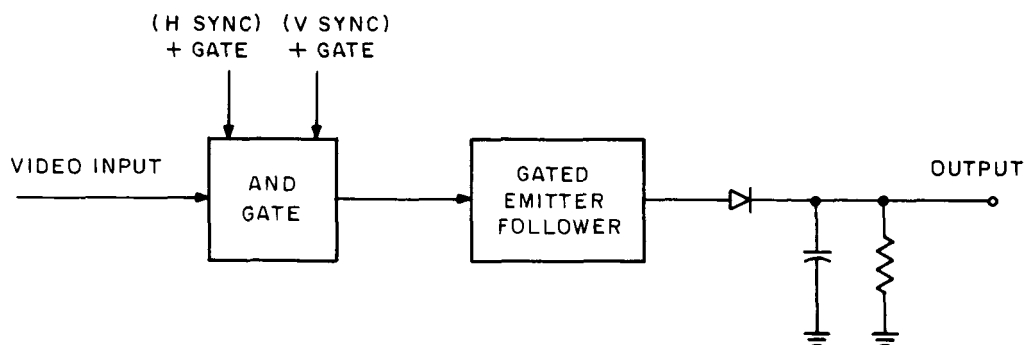entially peak detected and held on the output capacitor. The circuit provides video level information in the form of voltage differences rather than the actual voltage having any meaning, because of this gating pedestal. This would be subtracted in the proposed model.

Tests performed with Model I show up to several hundred millivolts difference between high and low video levels. Figures V-18a and V-18b are photographs of typical differences detected with large video signals. The cursor in Figure V-18a is the small rectangle near the upper left-hand corner of the raster. The output is seen to be 1.140 volts. In Figure V-18b, the cursor was moved onto the upper left-hand corner image. The output is now 1.329 volts or a difference of 189 millivolts.
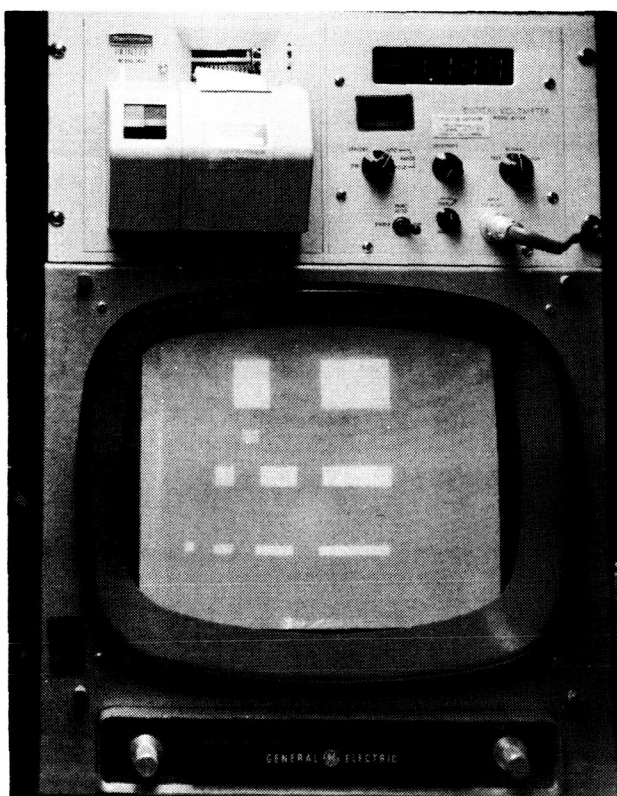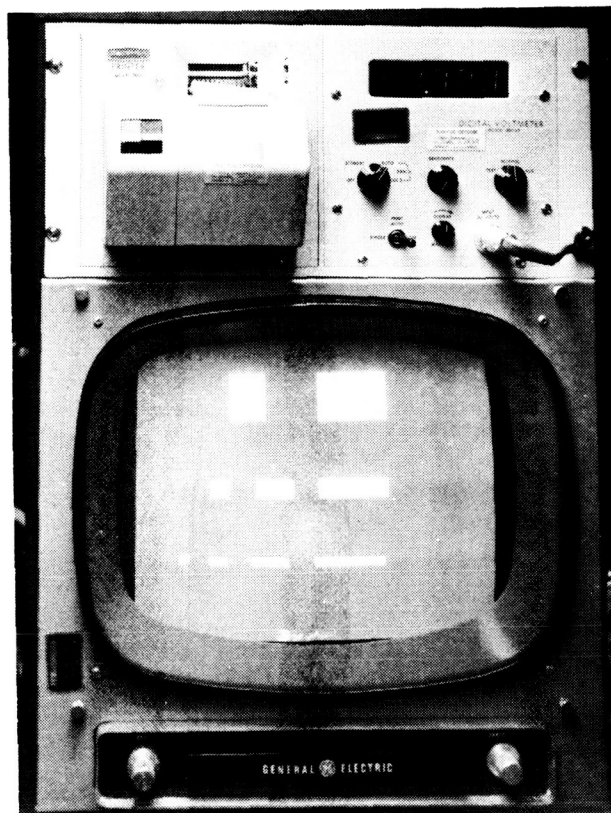
(a) Cursor on Background   (b) Cursor on Image

Figure V-18. Level Detector Laboratory Tests with Large Video Signals

Figures V-19a and V-19b show a similar setup with the video level reduced considerably. The difference under these conditions was only 14 millivolts. These particular tests were run with an image orthicon providing the video signals since the level detector responds only to a given video level and S/N and is independent of the sensor providing the signal.
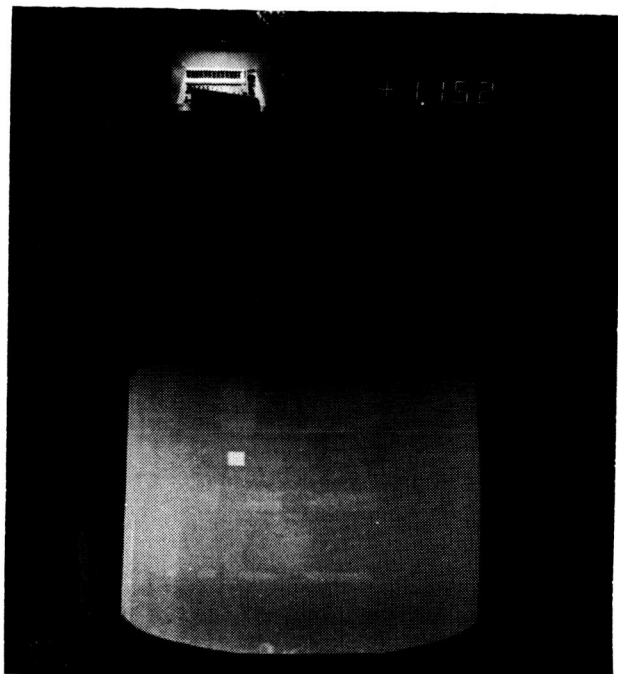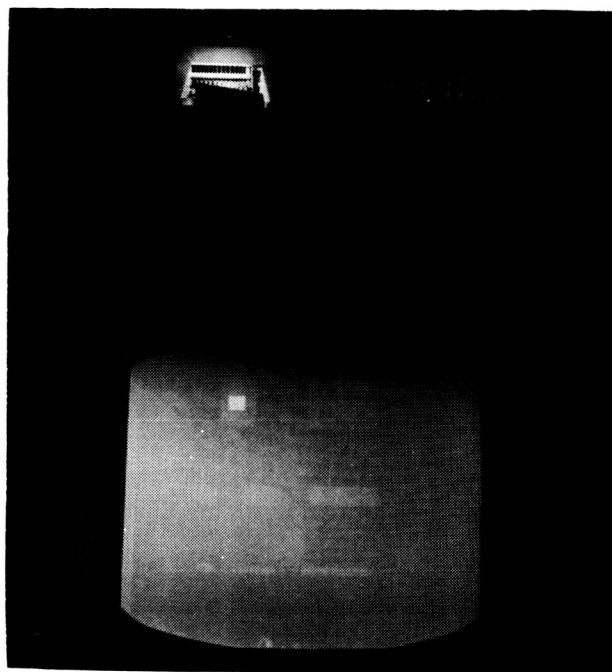
(a) Cursor on Background   (b) Cursor on Image

Figure V-19. Level Detector Laboratory Tests with Video Level Considerably Reduced
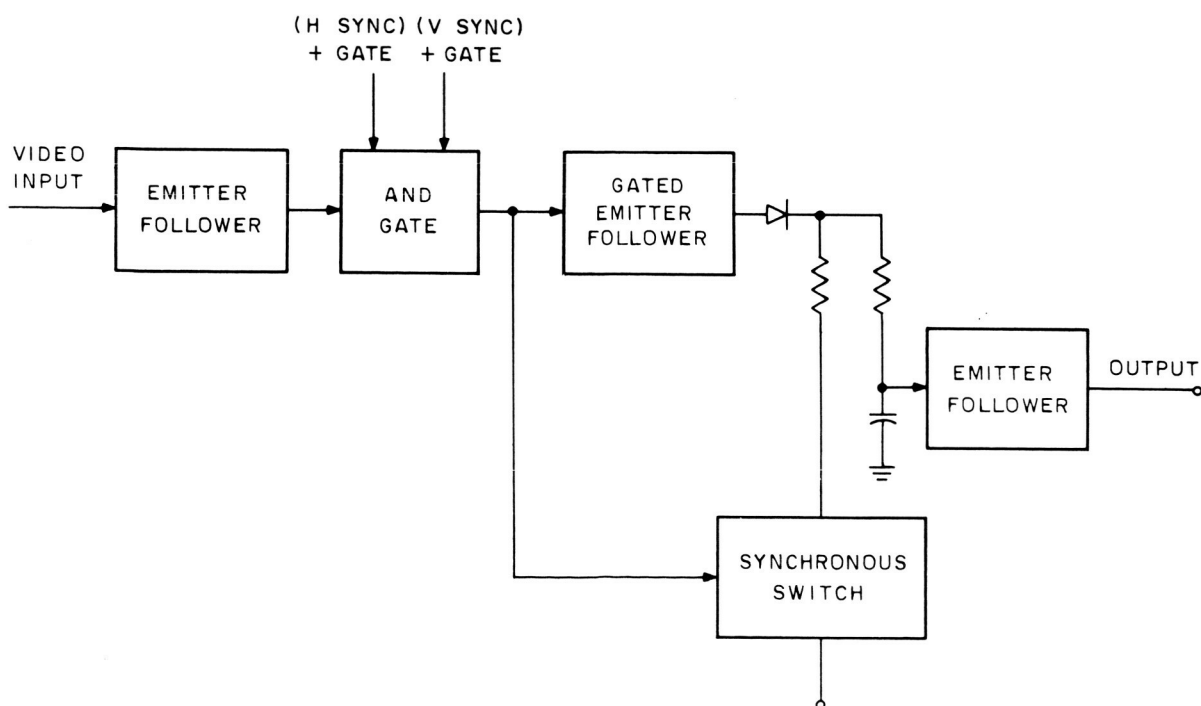

Figure V-20. Block Diagram of Video Gating and Level-Detector Circuit for Model II

Quantitative measurements relating actual video level, S/N, and output differences were not made. Results predicted by the analysis, which are quite often hard to realize practically, were approached in sensitivity but not accuracy. The main contributing cause of this was that peak detection (which this circuit approaches) is not what is desired, but suffices to determine the feasibility of the approach. A second shortcoming of Model I is its sensitivity to gating pulse width because it averages during the gated off time also.

With the AND gate technique confirmed, Model II was constructed to provide the proper level detection method and to provide a more controllable cursor injection. Figure V-20 is the block diagram for Model II. In this model the video input was sent through an emitter follower for isolation.

The gate pedestal was also coupled to the synchronous switch as described in paragraph 4. This action causes the averaging capacitor to average during the on time only and also prevents the circuit from peak detecting. An emitter follower was also added to the output to provide a lower output impedance and a longer discharge time constant for the averaging capacitor. The circuit is operating properly up to the level detector, but, in the few tests made, the level was still sensitive to gating pulse width and therefore, appeared to be decaying too much during the off time. The time constants described previously have still not been met, and this is probably the cause. There are no indications that Model II will not perform as expected when adjustments have been completed.

7. Display and Readout Instruments

The monitor used for this application should be large enough for convenient viewing by an operator even when he is several feet away from the screen. For consistency with the mounting of other electronics units of the operator's position, the monitor should be rack-mounted. The General Electric Model 4TH26B1 monitor, or an equivalent, is recommended. This rack-mounted model uses a 17-inch picture tube and can be obtained with a specially coated polarized glass faceplate to reduce glare.

A digital voltmeter is recommended as the readout device since it is convenient to use and provides a high degree of accuracy. In this application a possible limitation, applicable to most digital voltmeters, is the linear relationship between the input voltage and the numerical readout. With a conventional voltmeter, special nonlinear scales can be designed to modify the signal-level-to-temperature relationship as desired. However, these limitations of a digital voltmeter can be overcome by using either the graphical or the electronic level-temperature conversion technique described previously.

The Beckman Model 4011VP digital voltmeter, or an equivalent, is considered suitable for this application. This instrument provides a four-digit readout and automatic ranging for plus or minus voltages up to 999.9 volts. An internal standard cell is provided for test purposes. A printer such as the Beckman Model 1453 is a desirable accessory instrument which can be used in conjunction with a digital voltmeter to provide a printed record of the measured voltages. Rack-mounted versions of the Beckman digital voltmeter and recorder are shown in Figures V-18 and V-19. These photographs also show the General Electric 17-inch rack-mounted monitor.

8. Conclusions

From the analyses and the laboratory tests performed, it appears that a video gating system and level detector can be constructed to measure the level of a selected portion of a video signal to an accuracy of better than one percent. The tradeoffs relating averaging time, S/N, and confidence for a one-percent accuracy do not impose unreasonable restrictions. Conversion of this video level measurement to an equivalent temperature can be done graphically or electronically. Although no tests were performed, the electronic method has been briefly analyzed and it appears possible to obtain the required accuracy.

With the uncertainties of all the contributing functions held to one percent, and assuming that the IR sensor provides the specified S/N, a temperature readout accuracy of 1°F could be obtained. Measuring component temperatures using the entire automatic video processing technique described appears feasible. An additional benefit derived using the electronic gating technique is the potential capability of making direct real-time temperature comparisons of several components simultaneously. As many processors as desired could be added to operate simultaneously on different portions of the video signal from one IR vidicon. The extended capability and flexibility of such a system become quite attractive.

E. Optics

1. General Requirements

The IR system is required to detect temperature gradients at ranges varying from 1 to 72 inches from the lens. Three different sized objects are specified; this means that three different focal length lenses are necessary. The following effective focal lengths: 2.857 in.; 4.5 in.; and 1.0 in. (microscope objective type for examining microcircuits) will meet this requirement. Figure V-21 is a diagrammatic portrayal of the field-of-view and focus requirements of the system with a list of the characteristics of the three lenses. The lenses for this application must have high resolution across the field, good contrast, high speed (low F number) for low-temperature detection, and high transmission efficiency. The lens designs presented here should provide a high-quality image to show the circuit or component in adequate detail for inspection.

The spectral band chosen will be dependent on the sensor used. Approximate spectral bands for typical IR transmitting materials are shown in Table V-1. The tube recommended for this application is the GE Z-7808. The lenses described later have been developed using the specifications for this tube. A germanium filter with suitable antireflection coating is recommended for use with the Z-7808 IR vidicon. This filter blocks reflected energy at short wavelengths so that the vidicon senses only radiated energy from the scene.

2. Specific Design Considerations

Based on the general requirements discussed above, preliminary specifications for lenses 1 and 2 were established. These are given in Table V-2. Certain design considerations more specific to these lenses are presented in the following paragraphs before the lenses are described.

RECTANGULAR FIELD-OF-VIEW

OBJECT PLANE

D_o

IR LENS

ℓ_o

ℓ_i

IMAGE PLANE (RETINA)

D_i

USEABLE RETINA
AREA = 0.6 x 0.8 in.
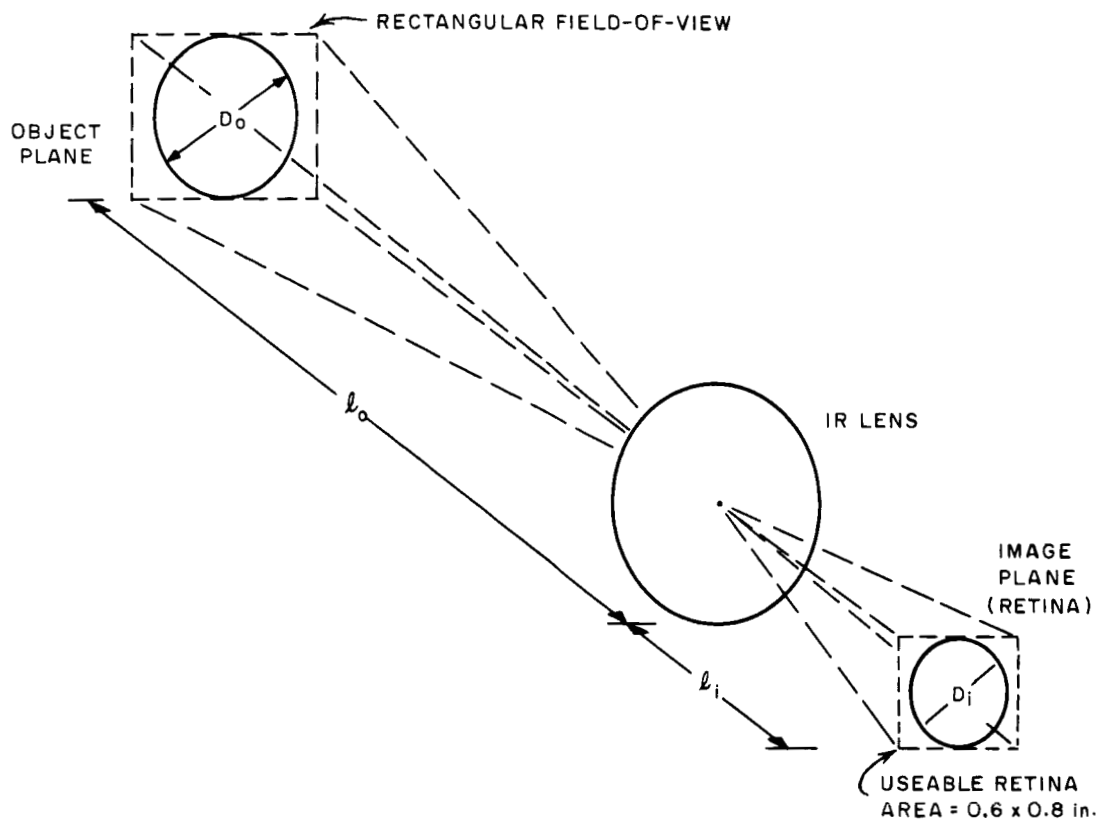
	Object Diameter D_o (inches)	Image Diameter D_i (inches)	Magnification m	Object Distance ℓ_o (inches)	Image Distance ℓ_i (inches)	Effective Focal Length
Lens 1	12	0.6	0.05	60	3.0	2.857
Lens 2	1	0.6	0.6	12	7.2	4.5
Lens 3	0.125	0.6	4.8	1.21	5.8	1.0

Figure V-21. Field-of-View Considerations for IR Lenses

TABLE V-1

APPROXIMATE SPECTRAL BANDS FOR TYPICAL IR TRANSMITTING MATERIALS

Material	Spectral Band (microns)
Sapphire	0. 3 to 5
Silicon	1. 4 to 9
IRTRAN AB-I	1 to 9
IRTRAN ABC-II	1 to 15
Barium fluoride	0. 3 to 12
Arsenic Trisulfide	0. 6 to 12
Germanium	2 to 20

TABLE V-2

PRELIMINARY OPTICAL SPECIFICATIONS (NOMINAL)

		Lens 1	Lens 2
1.	Effective focal length (in.)	2. 8	4. 5
2.	Speed	f/1. 6	f/1. 6
3.	Spectral transmission (μ)	1. 5 to 5. 0	1. 5 to 5. 0
4.	Resolution over 2. 5- to 5.0-μ spectral band (line-pairs/in.)	400	400
5.	Frequency response desired at 25 line-pairs/in.	98% across 12° field	98% across 6° field
6.	Object distance and range (in.)	$60 \begin{cases} +12 \\ -40 \end{cases}$	$12 \begin{cases} +8 \\ -0 \end{cases}$
7.	Overall field of view (maximum to corners of 1-in. diameter retina) (deg)	20	8
8.	Antireflection coating (both)	Double layer peaked to 3. 8 μ	
9.	Mounting (both)	Plain cell, black anodized aluminum, with threads as required for camera installation	
10.	Data (both)	Furnish transmission curve over spectral passband	

In general, a refracting system performs better than a reflecting system at the shorter focal lengths. The refractor gives a more solid image because the center of the lens is the best corrected part of the lens, whereas the reflector has a hollow core except right at the point of focus. If the reflector is slightly out of focus the image has a hole in it. The refractor has a flatter field of view which is an important factor in maintaining high resolution across a 12-degree full field of view. Even reflectors require one to three refracting elements when used at these fields of view. The reflector is a more difficult optical system to assemble than the refractor. For these reasons a refractor is recommended for lenses 1 and 2.

The 1.5- to 5.0-μ spectral band was chosen for the preliminary specifications based on possible use of reflected energy in the 1.5- to 2.0-μ band for alignment and focusing. This technique is described as System No. 4 in the section on IR camera focusing and alignment. A wide spectral band, say from 1.5 to 5.0 μ, presents many design problems. Lens materials (see Table V-1) whose dispersion values will compensate one another in the achromatized lens are relatively unavailable. Si and BaF$_2$ can be used together but resolution requirements cannot be assured. Off-axis resolution also suffers. The EFL of lens 1 will vary from 2.857 in. at 3.7 μ to 2.815 in. at 1.68 μ when these materials are used, owing to their different indices of refraction at these wavelengths. The modulation frequency response of the lens would be low over a wide spectral band.

Instrument performance can be improved considerably by narrowing the spectral passband. The reduced passband allows more efficient control of the energy. For example, the 2.6- to 4.1-μ band actually covers 90 percent of the target energy, tube response, and filter response. By narrowing the band, good chromatic correction can be achieved and the resolution is better than 400 line-pairs per inch across the field. The lens should now have a resolution considerably above that of the tube and the modulation frequency response should be at least 98 percent at 2 line-pairs/mm.

The wave band discussed above allows the use of Ge and Si, probably the best combination for chromatic correction. These materials have high indices and fewer elements are required to obtain the same power lens, resulting in better energy transmission. Here, too, the lens surfaces have less curvature so that the antireflection coating is more uniform. This combination of materials obviates the requirement for an extra piece of Ge for use as a filter when only the passband from 2 μ on is used.

High-index optical materials must be antireflection-coated. The transmission of uncoated Ge is only 46 percent; with an efficient coating it can approach a peak value of 98 percent. Figure V-22 shows a typical spectral transmission curve for a Ge filter coated on both sides with ZnS.

For a narrow passband, a single layer coating will provide a high-efficiency system. If a wide passband is required, two-layer coatings are required for efficient transmission.

In the Si-BaF$_2$ system, which would be required for focusing with reflected energy, two Si lenses and a Ge filter have to be coated; the BaF$_2$ lenses do not require coating. An antireflection coating is quarter-wave at the point where peak performance is required. In this type of lens, the peak is generally about 3.4 μ which means that the lowest surface reflection is obtained with a film thickness of 0.85 μ. The perfect antireflection coating should have an index which is the square root of the
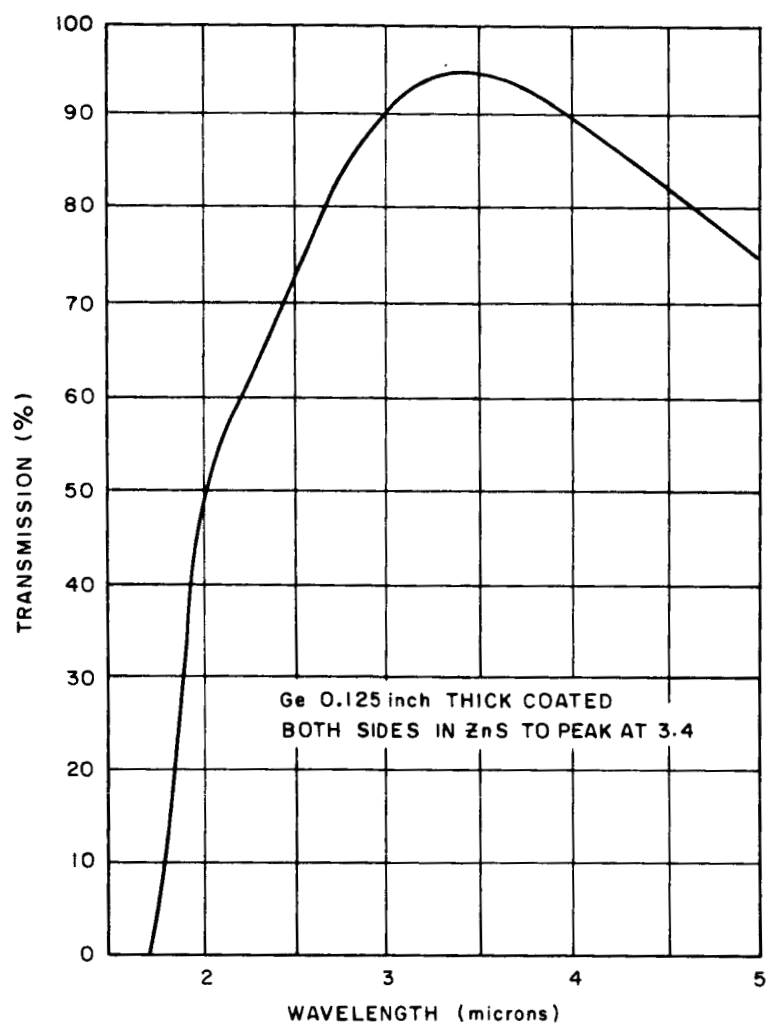
Figure V-22. Spectral Transmission Characteristics of a Coated Germanium Filter

substrate index. The index of Si changes with wavelength as shown in the following tabulation:

λ (microns)	n
1.5	3.480
2.6	3.4375
4.1	3.4249
5.0	3.4223

With these various indices, a given coating material will obviously not match at more than one point which peaks the film transmission noticeably. The index of the film should be 1.85 for Si which has an index of 3.4287 at 3.4 μ. Here a material that can be thin-film deposited is needed; unfortunately, there is none. The closest is SiO which has an index of 1.90. Using this will yield quite good peak transmission (97 to 98 percent) but this falls off quite rapidly on each side of the peak. Figure V-23 shows the peak at 3.4 μ in this case with 98-percent transmission.

It will be interesting to take a look at a double-layer coating on silicon. As shown in Figure V-23 the peaked transmission is still quite high and the curve is broadened considerably. A comparison of the curves on Figure V-23 shows that double-layer coating offers a considerable improvement over the single-layer coating. In Figure V-24, the transmission performance of the Si-BaF$_2$ lens and a Ge filter coated with ZnS to peak at 3.4 μ is compared for the single-layer and the double-layer coatings.

If a Ge-Si lens combination is used, antireflection coatings are required for both of these materials. Transmission curves for a Ge lens with single- and double-layer coatings are shown in Figure V-25.

The transmission performance of the Ge-Si lens is shown in Figure V-26 with single-layer and double-layer coatings. Since the Ge-Si lens would be used for IR imaging in the 2.6- to 4.1-μ band, a double layer coating would be of less importance than for the Si-BaF$_2$ lens whose primary purpose would be to cover the broader band of 1.5 to 4.1 μ.

Characteristics of each of the three lenses for the infrared measurements system are as follows:

a. Lens 1; 2.857-inch EFL, f/1.6. This lens will be required to project an object 12 inches in diameter at a distance 60 inches from the lens onto the tube retina with a magnification of 0.05. A range of usable distances of from 20 to 72 inches is recommended.

With the object 24 inches from the lens, the retina will be 3.243 inches from the lens. The object size that can be seen in view is less than for the 60-inch distance but the conjugate foci are considerably different. In this case, resolution suffers to some extent because the lens is corrected for the 60-inch case. The amount of resolution loss cannot be determined until the lens is designed. This is not too serious because the magnification is now 0.27, giving a larger image.
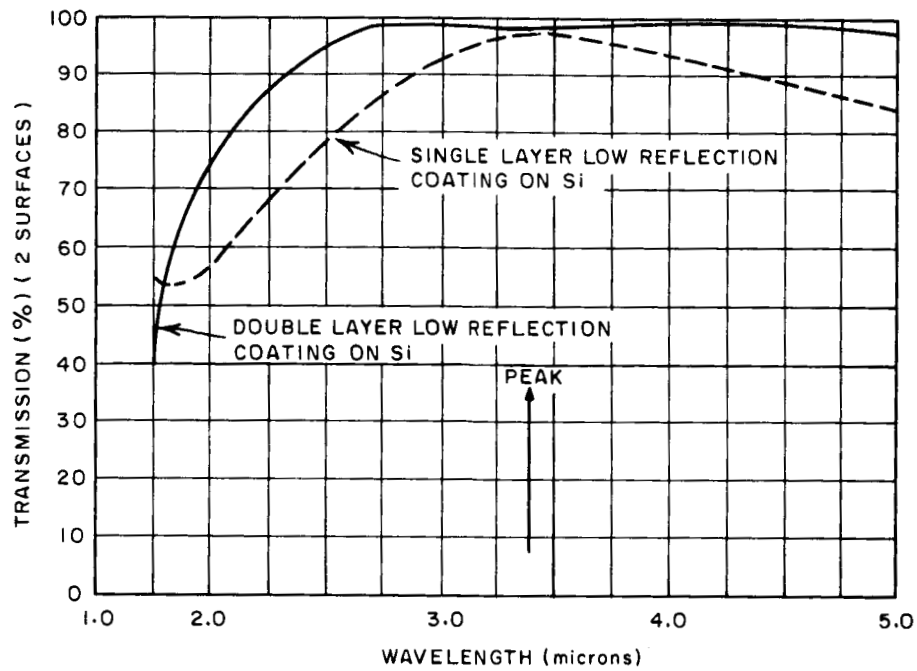
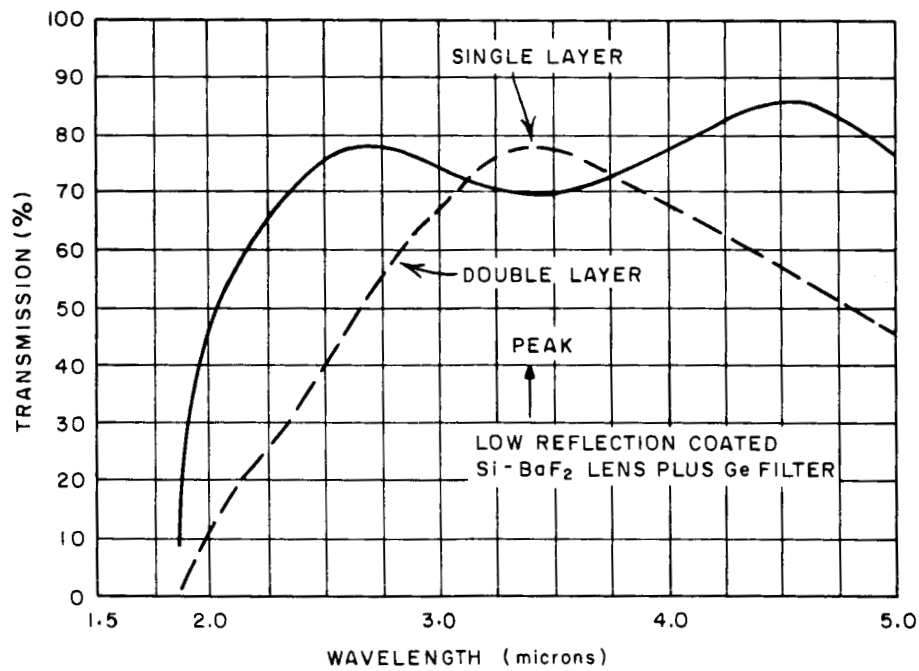Figure V-23. Antireflection Coatings for Silicon Lens

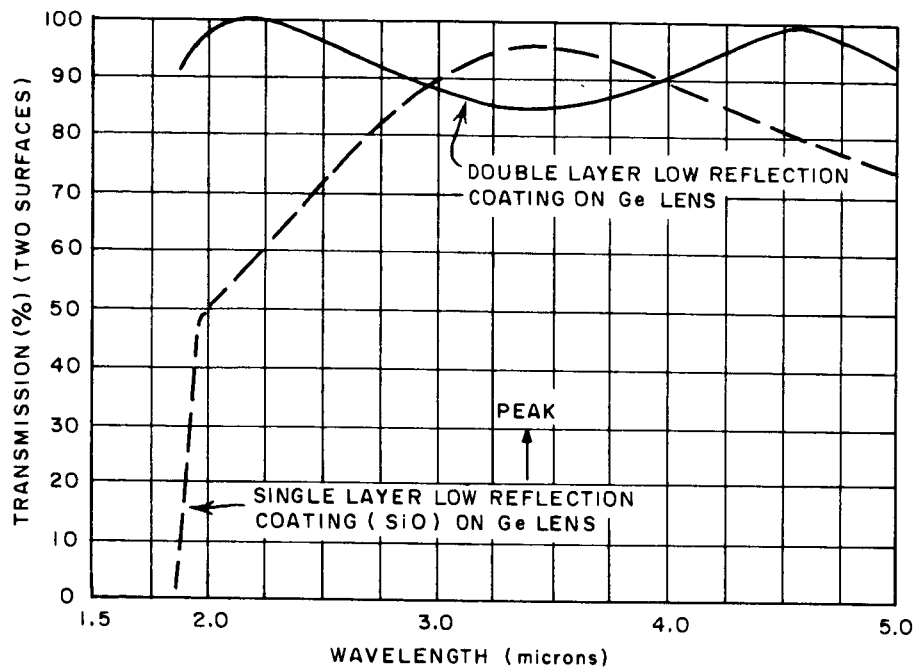Figure V-24. Transmission Characteristics of Si-BaF_2 Lens

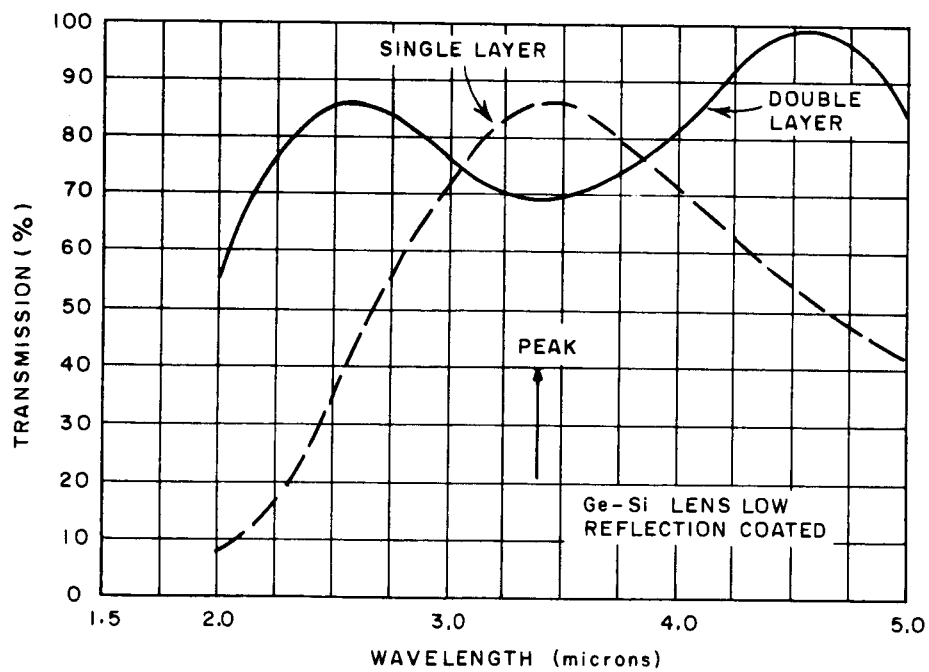Figure V-25.   Antireflection Coatings for Germanium Lens

Figure V-26.   Transmission Characteristics of Ge-Si Lens

If short wavelength transmission is not required for alignment and focusing purposes, the Ge-Si lens, discussed previously, should be considered. With anti-reflection coatings such as those described, good transmission characteristics can be achieved for the required spectral region.

Depth of field is based on the amount of resolution loss which can be tolerated. Assuming that an optical resolution of 250 line pairs/inch provides an acceptable image, the depth of field is ±3 inches for an object distance of 60 inches. Focusing accuracy requirements are discussed in section E-4.

b. Lens 2; 4.5-inch EFL, f/1.6. The lens for the 12- to 20-inch object distance with an object size of 1-inch diameter will be basically the same design as lens 1 except that it will be designed for shorter conjugate foci and a narrower field of view. The antireflection coatings will be the same as for lens 1. (Reflection coatings are discussed earlier in this section.)

Brief calculations show that the depth of field for this lens is ±0.120 in. for a 40 percent reduction in resolution. If the depth of field is ±0.06 in., no deterioration in resolution occurs. This lens should perform well with a good depth of field commensurate with object size. Adjusting the lens for good focus can be accomplished by utilization of one of the alignment and focus systems discussed in section E-4.

c. Lens 3; 1.0-inch EFL, NA > 0.54 (Figure V-27). The optics for the examination of the microelectronics will be actually a low-power microscope. The object size of 0.125 inch when used with the 0.6-inch retina size gives the system a magnification of 4.8. Since this lens is a microscope objective it should be used near the designed conjugates.

For the lens of 4.8 magnification, the EFL can be 1.0 inch with a front focal distance of 1.21 inches and a back focal length of 5.8 inches. The preferred optical design in this case is a reflecting system ratioed up from a standard reflecting objective. Some of these have a refracting element in the system to improve the correction. If this is the case, it can be made of Ge which will eliminate the need of a Ge filter, as mentioned earlier. This lens should have a numerical aperture (NA) of at least 0.534, or larger if possible. This is approximately equivalent to a f/1 lens. It will resolve at least 2000 line pairs per inch at the object.

This lens would be classed as an inspection tool which requires that the object be rigidly located and centered in a fixture. The image and object distances would be maintained within quite close distances and the focusing mechanism would cover only a short range, say approximately ±1/4 inch travel. The fixture for holding the microcircuit can be made removable so that it can be replaced by other fixture holders for other microcircuit configurations.

3. Optical Cold Shield

The design for the IR lens mounting assembly should provide for an internal cold shield to reduce unfocused radiation incident on the IR vidicon retina. One method to implement this feature is illustrated in Figure V-27 for lens 3. A similar configuration would be used for lens 1 and lens 2. A more detailed description of this cold-shielding technique is included in section V. F.
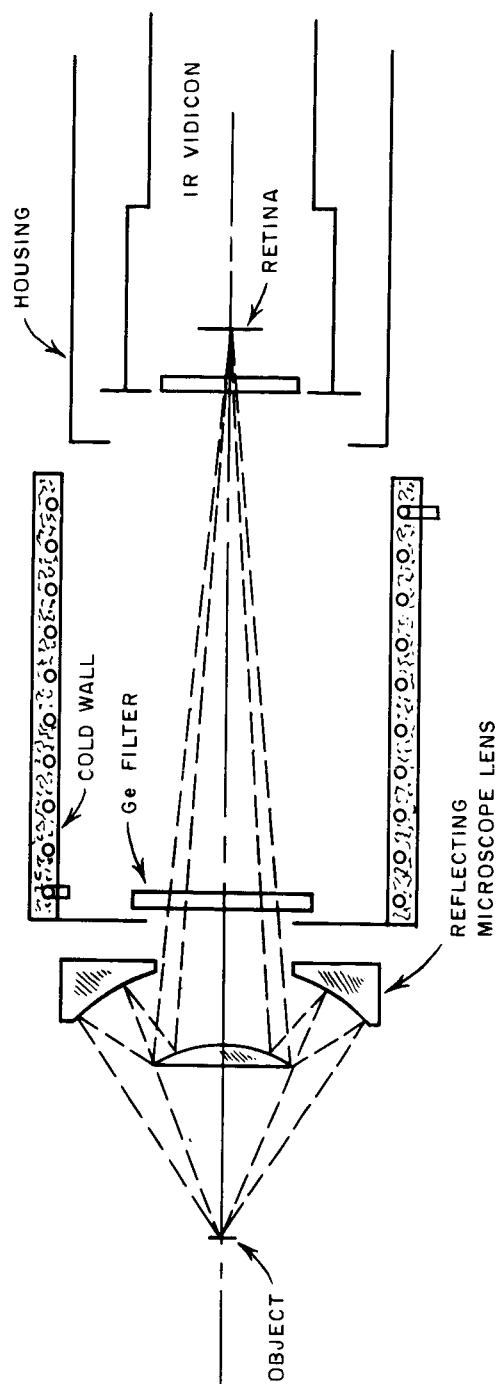
Figure V-27. Schematic of Lens for Viewing Microcircuits

4. IR Camera Focusing and Alignment Methods

Investigations of various focus and alignment techniques have been conducted. A simple telescopic viewfinder attached to the TV camera head is not adequate at short ranges because of parallax. A primary goal is to determine methods which do not require operation of the test circuit to provide an image on the monitor. This feature will permit measurements of transient circuit conditions during the warmup period. Five alternative systems of varying degrees of sophistication were investigated and are summarized in Table V-3. The various techniques were studied considering their primary application with lens 1. The five alignment and focusing systems described below could also be applied to lens 2:

a.   System No. 1. In this system, the image of the operating circuit appears on the monitor, and focus and alignment are adjusted by observing the monitor image. As an alternative, the calibration source may be substituted for the test circuit.

The system consists of the basic camera with the cooled lens mounted on the front end as shown in Figure V-28. This lens is mounted so that its position with respect to the IR tube retina can be adjusted by means of a simple screw and locking device.

b.   System No. 2. This system consists of the basic camera with the cooled lens mounted to the front end and a retractable (or detachable) light-spot projector attached to the lens housing, as shown in Figure V-29. The spot-projector lens and mirror optical axis are collinear with the optical axis of the IR lens between the object and the projection mirror. Object centering (alignment) is achieved by adjusting the position of the camera or the object so that the projected light spot falls at the desired position on the object.

Focusing is achieved in the same manner for this system as in system No. 1; that is, the image picture produced by the energized circuit (or the calibration source) is observed while the lens is adjusted for optimum focus.

c.   System No. 3. This system consists of the basic camera with the cooled lens mounted on the front end. The lens is focusable on a slide which is controlled by a micrometer head and then locked in place. The camera head is mounted on a commercially available slide so that the object distance of the head and lens assembly can be controlled. By referring to a curve, the object-to-lens distance and the lens-to-retina distance can be read. The lens-to-retina distance can be set by the micrometer head and the lens-to-object distance adjusted by moving the axial slide and measuring the distance with a collapsible rule (see Figure V-30).

This method will furnish a good experimental instrument which can be used in a number of different ways such as in the laboratory, in the field, or with a vacuum chamber. It will require only very ordinary measurements to determine target distance but this is a usual method in an experimental setup.

For a particular image distance of say 3 inches, the required accuracy of setting the object distance from the lens is ±3 inches with a degradation of resolution from 400 line-pairs/inch to about 250 line-pairs/inch. Since the measurement accuracy can easily be held to ±1/4 inch under the worst conditions, the shift in the focal plane with the object near the 60-inch distance is so small that the resolution will approach 400 line-pairs/inch.

TABLE V-3

AIMING AND FOCUSING SYSTEMS FOR IR MEASUREMENTS

|	Aiming and Focusing Method	Spectral Band, IR Lens (μ)	Relative Merit
System No. 1 Figure V-28	Observe thermal image of test object on monitor, or substitute calibration source for test object.	2.6 to 4.1	Satisfactory for steady-state thermal conditions
System No. 2 Figure V-29	Aiming technique uses built-in projector, produces light spot at object plane in center of view field. Focus by observing thermal image of test object or substituting calibration source for test object.	2.6 to 4.1	Satisfactory for steady-state thermal conditions
System No. 3 Figure V-30	Light spot projector for aiming. To focus, measure object distance, consult graph or table, and set image distance on micrometer focus scale.	2.6 to 4.1	Good experimental method. Aiming and focusing prior to heating test object
System No. 4 Figure V-33	Monitor image of test object obtained using reflected energy from flood lamp. Possibly refocus lens for imaging hot test object with self-radiant energy.	1.5 to 4.1	Questionable method due to change in focus distance at different wavelengths
System No. 5 Figure V-34	Visible reflex sight for aiming and focusing. Visible and IR lens mechanically coupled for simultaneous focusing.	2.6 to 4.1	Good method for repetitive measurements beyond experimental stage
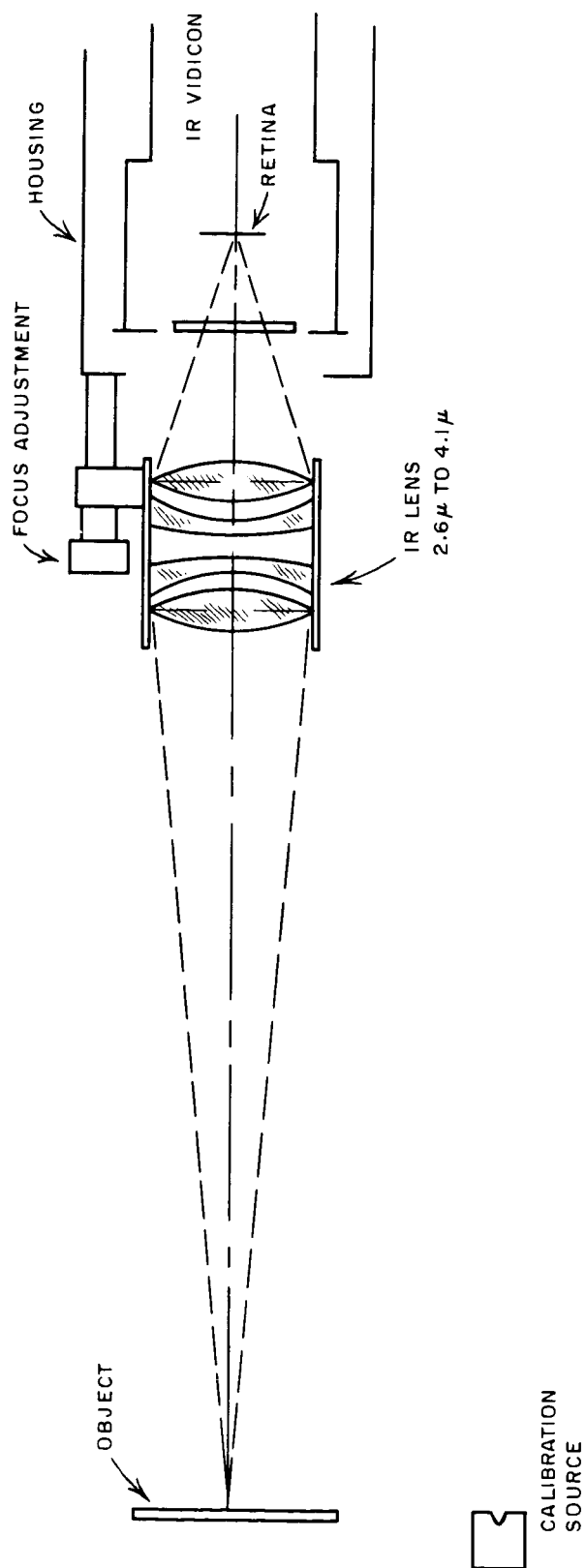
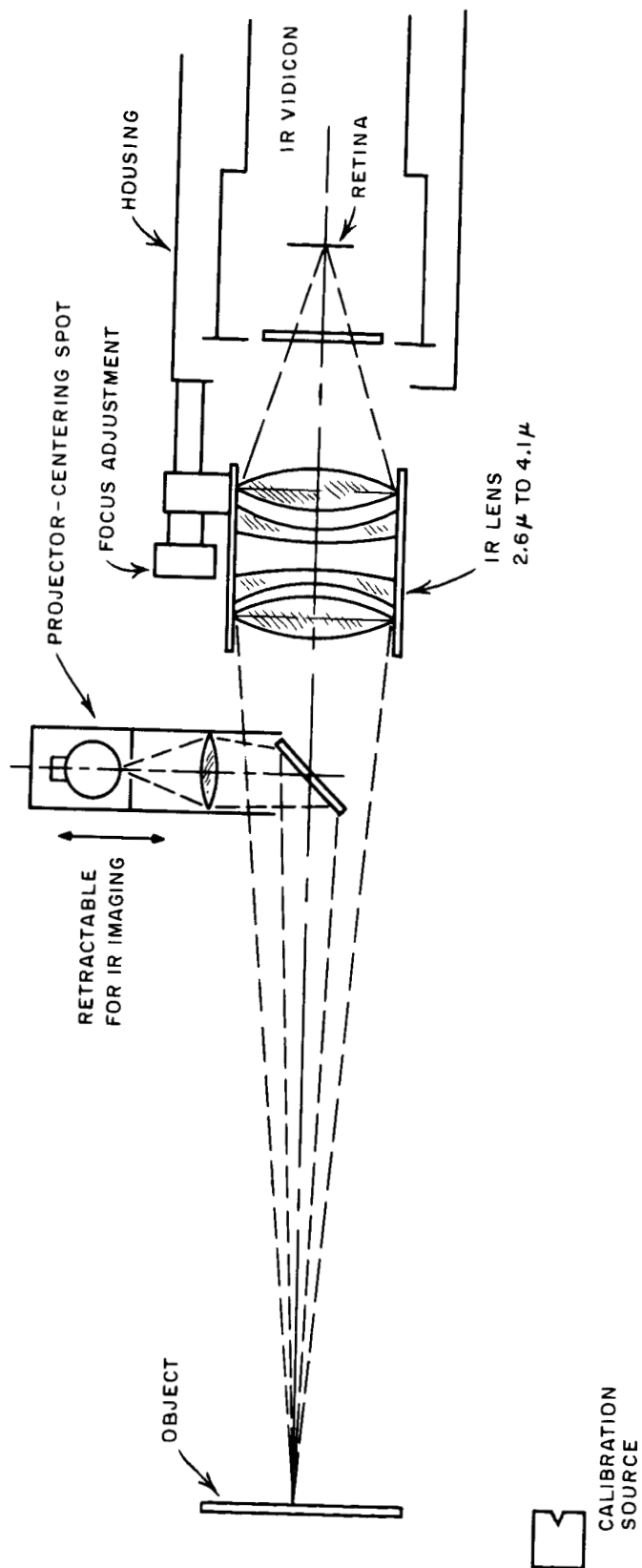Figure V-28. Focus and Alignment System No. 1
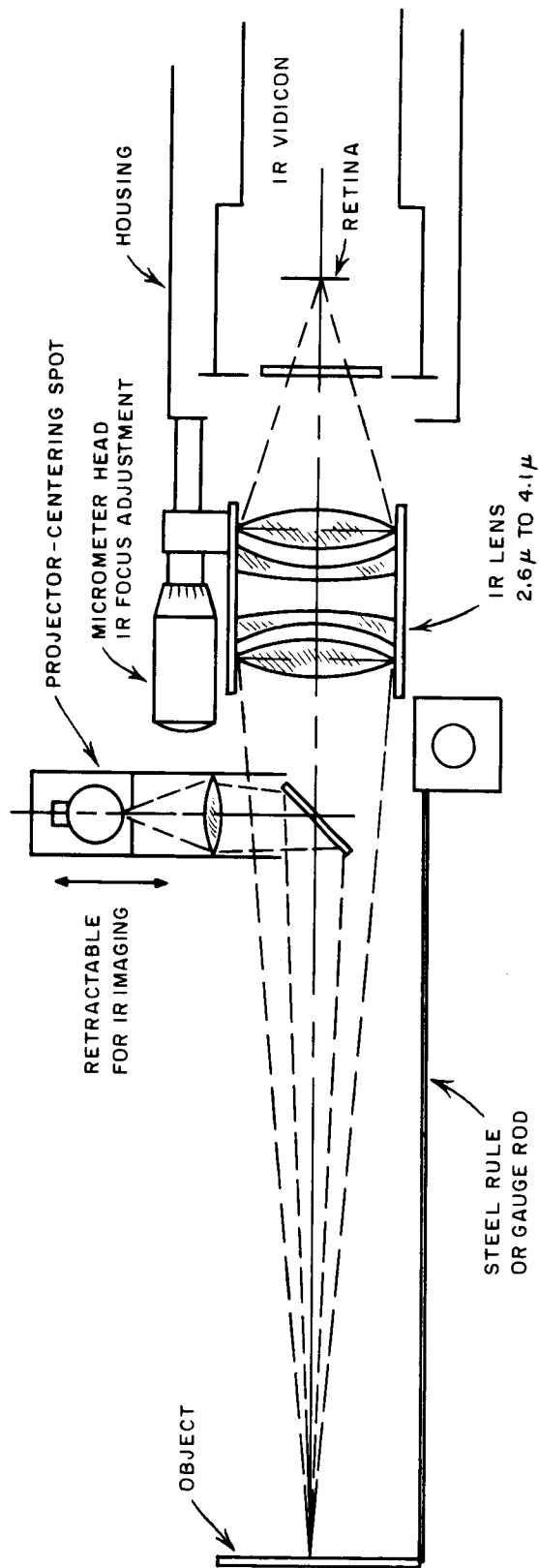
Figure V-29. Focus and Alignment System No. 2

Figure V-30. Focus and Alignment System No. 3

With the object at the 20-inch distance it is reasonable to expect that the object distance can be measured to within ±1/8 inch, which is well within the focusing requirements for maintaining resolution. Figure V-31 shows the image-to-object distance relationships. Figure V-32 shows the object-measuring tolerance necessary to hold the lens resolution to its design limit of 400 line-pairs/inch. It is also necessary to center on the spot that is to be inspected. A small spot projector will project a spot on the center of the area to be inspected. This small projector can be retracted outside of the IR field of view during IR image measurements.

A variation of system No. 3 would use a gage to position the object at a precise distance (within ±0.02 inch) from the lens. The number of gages can be set at certain required distances, say six gages. This variation of system No. 3 was considered during the design study but was felt to offer no particular advantage, and it is slightly more expensive. This method would require a table of object distances (Table V-4) to maintain the above accuracies.

d. System No. 4. This system uses reflected light in the spectral band from 1.5 to 2.0 μ on the object for focusing. This method requires a light source to illuminate the object as shown in Figure V-33. However, the change of focal length with the optical materials index change at different wavelengths introduces poor accuracy.

The index of Si (this is estimated for a Si element alone) at 3.4 μ is 3.4287 and at 2.0 μ is 3.452. Two microns is the upper limit of the visible focusing spectral range and 3.4 μ is the peaked center of the spectral band. This difference in index shifts the object distance 10 inches toward the lens from a basic 60-inch object distance for an operational wavelength of 3.4 μ. Chromatic correction can reduce this considerably but there is still the danger of too great a shift for best resolution at 3.4 μ by focusing at 2.0 μ.

This brief analysis shows that the lens will be out of best focus. Also, the lenses for this system are more expensive because of the additional element and the design time for the wide spectral band. Obtaining a good focus at the light levels that can be used is also a problem because the objects have rounded shapes which are difficult objects to focus on under low-contrast conditions. Using a highly reflective resolution chart placed in the same plane as the object would improve this focusing condition in that the edges of the pattern would be sharp and of high contrast.

e. System No. 5. This system uses a reflex type of sight mounted just ahead of the IR objective. The sight consists of an objective with the same EFL as the IR lens, a reticle (with various patterns for centering the object) and a 4× eyepiece. Ahead of the sight and IR objective is a 45-degree mirror which reflects the object up into the sight since the sight is at right angles to the main instrument (see Figure V-34).

This is a convenient system to use because it can be aimed at any object and the focus control turned to bring the object into sharp focus; the IR objective is automatically in focus since both lenses are focused by the same control. The reticle could be constructed with centering lines which would be useful for aiming the IR camera at the desired portion of the test object. This sight is designed for the visible region where good correction, sharp images, and sufficient illumination are possible. The mirror is designed to swing up out of the way for IR use and it indexes against a
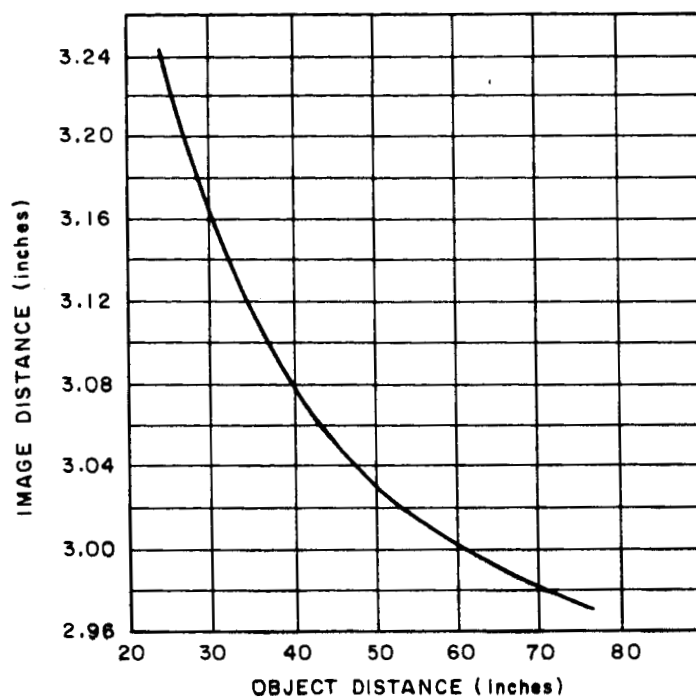
Figure V-31. Focusing Curve for Lens 1
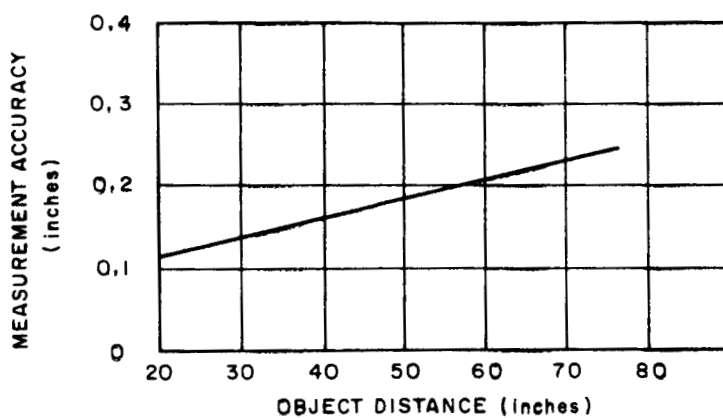
Figure V-32. Accuracy in Object Distance Measurement Required to Maintain
Resolution at Design Limit (400 line-pairs/in.) for Lens 1

TABLE V-4
OBJECT-TO-IMAGE DISTANCE

$$\frac{1}{m'} = \frac{1}{f} + \frac{1}{m}$$

$$m' = \frac{mf}{m + f}$$

Object Distance (inches)	Image Distance (inches)
24	3.24305
26	3.20969
28	3.18164
30	3.15772
32.5	3.13235
35	3.11094
37.5	3.09261
40	3.07675
45	3.05068
50	3.03014
55	3.01353
60	3.000
65	2.98834
70	2.97856
72.5	2.97420
75	2.97014

Figure V-33. Focus and Alignment System No. 4
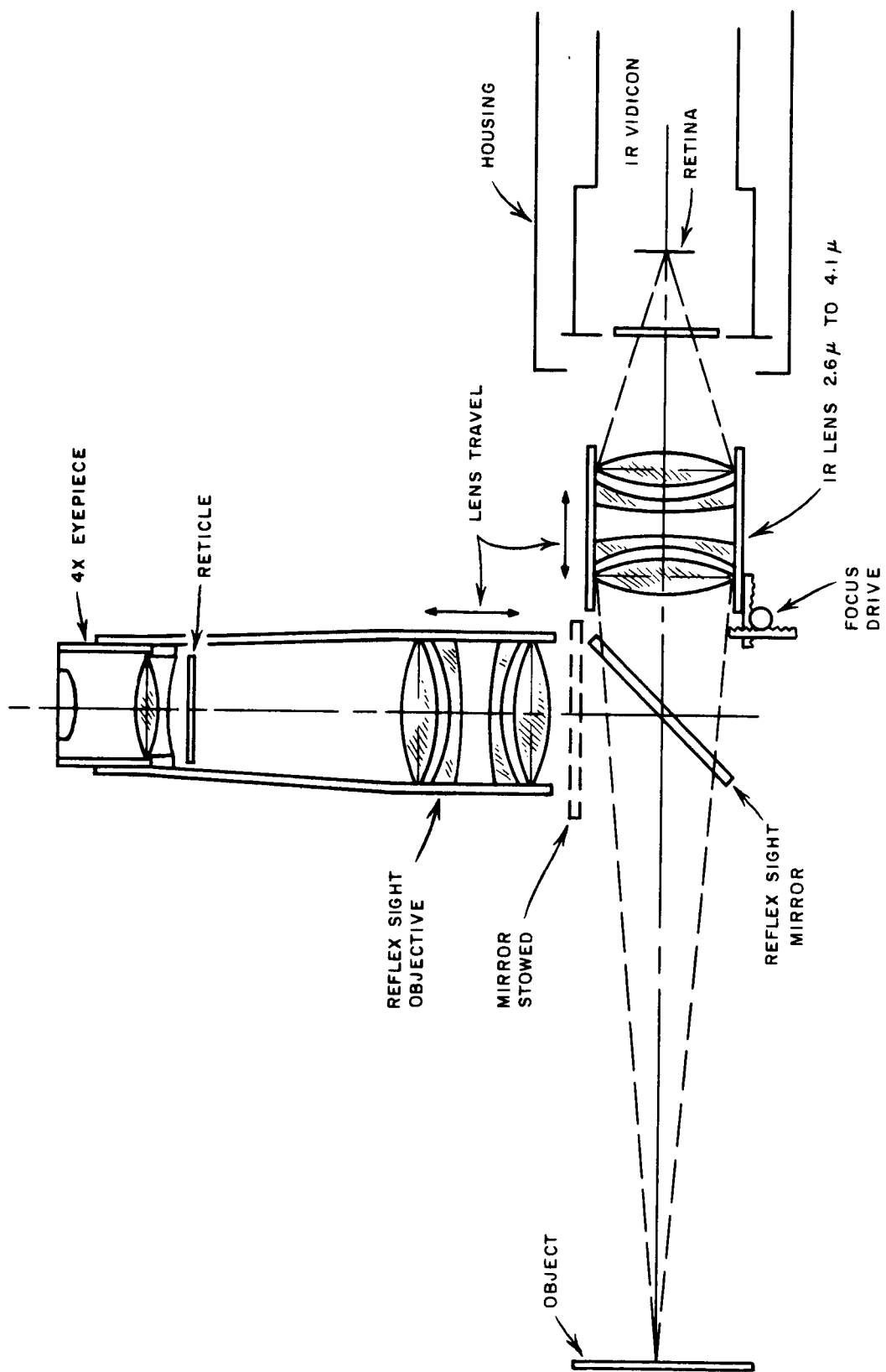
Figure V-34. Focus and Alignment System No. 5

positive stop in the down position to insure proper alignment of the visible and IR systems for the sighting operation.

This system will locate the object (at the 60-inch basic distance) within ±7/8 inch which is not quite as good as system No. 3, but it is well within the allowable ±3-inch location. This can be improved with a higher magnification eyepiece if necessary.

5. Vacuum Chamber Operation

One technique for viewing circuits in a vacuum chamber requires a sealing window set in the wall of the chamber which will transmit from the visible for the reflex si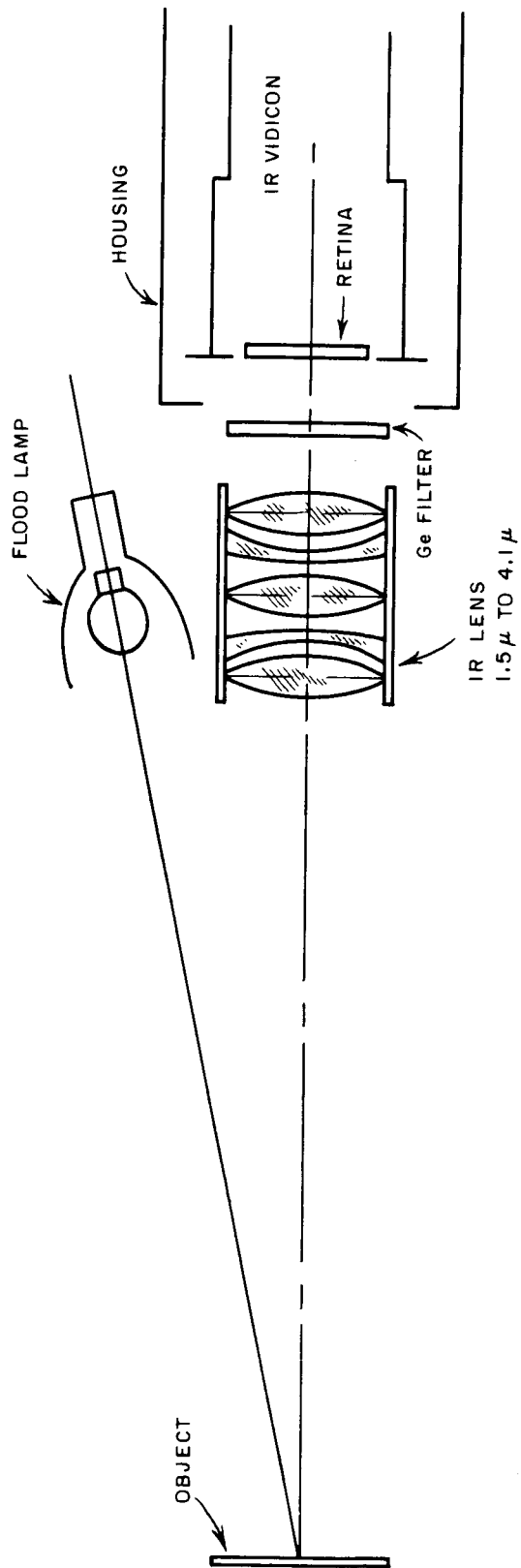ght through the IR. This material can be sapphire, BaF_2 or IRTRAN V. Putting this window in the object end of the system will extend the object focal distance by 0.103 inch for the sapphire window, 0.118 inch for the BaF_2 window, and 0.153 inch for the IRTRAN V window at 3.4 μ. The path increase in the visible is 0.109 inch for the sapphire window, 0.121 inch for the BaF_2 window, and 0.150 inch for the IRTRAN V window. The error caused by the two wavelengths is 0.006 inch for the sapphire window, 0.003 inch for the BaF_2 window, and 0.006 inch for the IRTRAN V window, all of which are negligible.

Generally, the window in a vacuum system is part of the vacuum system and is sealed in the wall. This avoids making a vacuum seal and moving or disassembling the equipment at every run. This also keeps the IR vidicon system independent so that it can be easily moved about for alignment with any target, even when a setup is in the vacuum chamber and the system has to be used temporarily to look at another target. This also makes it possible to move the system about when used with the vacuum chamber to look at more than one target that is inside just by swinging it at a slight angle to the window. The focus and alignment can always be checked by the reflex sight. The diameter of this window should be about 5 inches OD, 4.5-inch CA to insure sufficient aperture for future lenses such as the 4.5-inch lens at f/1.6. If this lens has a slower speed the clear aperture diameter safety factor will be that much better.

As an alternative, the window can be put in the front end of the camera assembly and sealed in place. This front end would have a flange for sealing against the vacuum chamber. This means that the camera would have to be rigidly supported in place and squared against the side of the vacuum chamber in order to keep a vacuum seal. This is an operational problem that would have to be resolved prior to equipment installation. Considering the above factors, it is recommended that the IR window be used for vacuum chamber operation.

F. Cryogenics System

1. Requirements

Operation of the Type Z-7808 infrared vidicon requires that the retina be cooled to liquid nitrogen temperatures. For this purpose a copper finger thermally connected to the retina protrudes outside the tube and can be immersed in liquid nitrogen. A very simple approach is to use an open mouth dewar filled with liquid nitrogen for cooling the copper finger; however, the dewar must be refilled every 30 to 60 minutes. Extended operation can be achieved by using a cryogenics system

consisting of two dewars, a small cell dewar attached to the vidicon cold finger, and a larger storage dewar. Automatic transfer of liquid nitrogen to the cell dewar permits operation for a period of time limited only by the capacity of the storage dewar.

Discussions with NASA representatives during the study indicated the desirability of providing for 2-hour operation between refills of the cryogenics system. To meet this requirement, it is estimated that the storage dewar should have a 2-1/2 liter capacity. This estimate is based on a consumption of 1.0 liter during an initial 30-minute cool-down interval and 1.5 liters for an additional 2-hour operating interval.

In addition to the primary requirement of cooling the IR vidicon retina the cryogenics system also provides a means of cooling the IR lens housing. The walls of the lens housing behind the lens constitute a source of unfocused IR radiation which decreases the IR vidicon sensitivity to scene radiation transmitted and focused by the lens. For maximum effectiveness the lens housing should be cooled to a temperature well below ambient; it is estimated that a temperature of approximately -50°C is required.

Techniques for reducing the undesirable effects of unfocused radiation have been investigated. The most practical method is to use a double-walled construction for the lens housing. The inner wall is cooled to the desired temperature and thus serves as a cold shield to block unfocused radiation. An attractive method for cooling the inner wall of the lens housing is to use cold nitrogen vented from the cryogenics system, as shown in Figure V-35. The cold gas is circulated through a coil surrounding the cold shield and then vented to the atmosphere. If the required cooling can be achieved by using only the volume of gas normally boiled off by the IR vidicon and cryogenics system, the cold shield requirements can be met without additional consumption of liquid nitrogen. A good insulating material such as closed-cell, Freon-filled, urethane foam should be used around the cold shield. The transfer line carrying cold gas to the cold shield should also be insulated; wrapping the line with a closed-cell foam tape is a possible insulation method.

Specifications for a liquid nitrogen cryogenics system for an IR vidicon camera are listed below.

    a. Overall System

        1. Cryogenics configuration: Two dewars are required, a small cell dewar attached to the IR vidicon cooling finger, and a larger supply dewar attached to the camera head assembly. This system includes interconnecting lines as needed for liquid nitrogen transfer.

        2. IR vidicon heat load (exclusive of dewar losses): 15 watts.

        3. Operating time: 30 minutes cool-down plus an additional operating interval of 2 hours.

        4. Storage capacity: as required by items 2 and 3 above (2-1/2 liters is estimated).

        5. Liquid transfer: liquid nitrogen will be transferred using self-generated gas pressure. Automatic flow control is required to keep the cell dewar
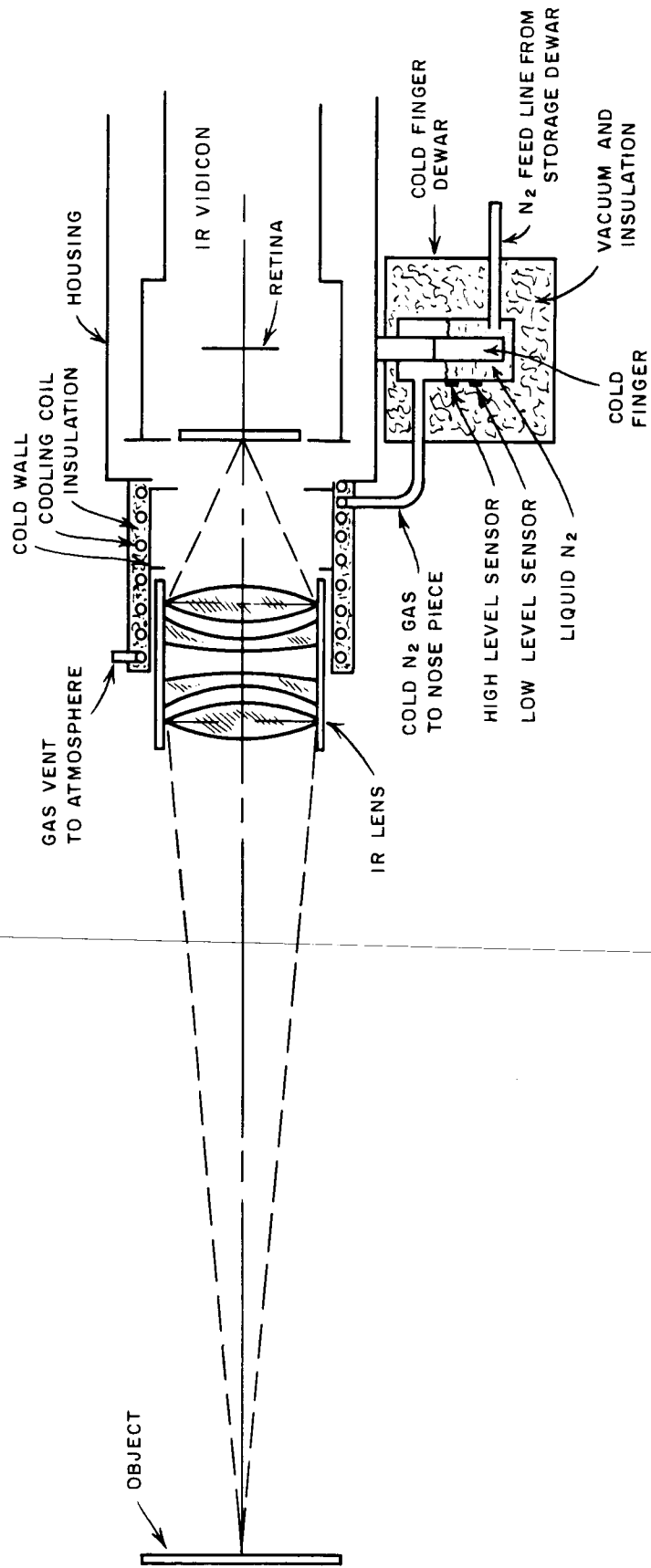
Figure V-35. Schematic of Optical Cold Shield Technique

filled with liquid nitrogen. In addition, a manual flow control in the form of a needle valve with a micrometer head (Hoke, Inc. series 280, or equivalent) will be provided for operation with the automatic control disabled.

6. Transfer line: a 24-inch length of flexible, vacuum-insulated line with bayonet fittings at each end will be included for liquid nitrogen transfer.

7. Connections: threaded connections for gas and liquid transfer lines will be standard AN fittings wherever practicable.

8. System mounting and orientation: the cryogenics system will be attached to the IR vidicon camera head assembly which is normally oriented with the cooling finger pointed down. The combined package (cryogenics and head assembly) will be mounted on a heavy duty tripod so that it can be aimed in both azimuth and elevation. Cooling must be maintained for angular excursions of 360-degree azimuth and ± 30-degree elevation.

9. Vent gas: cold nitrogen gas exhausted from the system is required for cooling optical elements. The vent port should be located near the cell dewar and be suitable for the attachment of a length of rubber tubing.

10. Operating environment: the equipment should be constructed using good commercial practices so that safe, reliable operation in a laboratory environment is assured for an extended time.

b. Cooling-Finger (Cell) Dewar

1. Dimensions: a compact size is desirable to permit freedom of travel for the tripod-mounted head assembly. When installed on the cooling finger the bottom of this dewar should extend no more than 8 inches below the centerline (longitudinal axis) of the camera head. Other dimensional requirements are imposed by the size of the vidicon cooling finger (0.625 in. diameter × 3.5 in. length outside camera housing).

2. Pressure seal: this dewar will have provision for sealing around the upper portion (stainless steel sleeve) of the cooling finger. A small positive pressure (2 to 3 psi) must be maintained internally so that a controlled flow of cold nitrogen gas can be obtained from a vent port for cooling nearby optical elements.

c. Supply Dewar

1. Size and configuration: dimensions are not critical, but it is desirable that this unit be attached to the camera head assembly in a reasonably compact configuration. The storage dewar will be located beside or above the camera head to avoid interference with the tripod mount.

2. Fill port: the fill port will be constructed to prevent excessive losses when the cryogenics system is rotated through the previously stated angular excursion. This port will be suitable for pressure filling from an external system. Provision for manual filling is also desirable.

3. Pressure relief: a safety valve will be provided for relief of excessive pressure.

4. Mounting brackets: mounting brackets, to be specified later, will be attached to the storage dewar.

2. Recommended System

A modified version of the Linde Company LNF-54A liquid-nitrogen cryogenic system is recommended. The LNF-54A system has been used successfully with previous GE IR vidicon cameras. Functions such as liquid transfer, pressure regulation, and automatic level control would be accomplished by the same methods used for the LNF-54A system. One modification involves changing the configuration of the storage dewar and reducing its volume from 5 to 2-1/2 liters. The smaller container is better suited for compact mounting on the camera head assembly.

A second variation from the LNF-54A system arises from the need to maintain liquid-nitrogen flow while moving the camera head through elevation angles of ±30 degrees. This requires mounting the storage dewar so that its axis is at an angle of approximately 30 degrees with respect to that of the camera head as shown in Figure V-4. Also, internal feedlines must be located to maintain liquid-nitrogen flow as the elevation angle is changed.

A fill port, located at one end of the storage dewar, is used for pressure filling of the storage dewar from an external liquid-nitrogen supply. The diameter of the fill port is kept small to avoid excessive liquid-nitrogen losses when the storage dewar is horizontal. Some flexibility would be gained by using a system which could be filled either manually, by pouring, or under pressure. However, the design effort required to provide this feature while maintaining good thermal insulation would probably increase the cost excessively.

Figure V-36 is a schematic diagram showing the operating principles of the recommended system. During operation, an internal electrical heater builds pressure in a storage dewar on demand from an external electrical circuit. A pressure switch in the external electrical circuit maintains the dewar operating pressure at the desired level, and a temperature switch set at -20°F prevents the heater from burning out when the liquid-nitrogen supply is exhausted. A solenoid valve in the vent line of the cell dewar allows off-on control of the liquid nitrogen feed. The flow control solenoid is actuated by high- and low-level sensing thermistors located in the cell dewar. The liquid level control switching is provided by the flow control box. The vent gas due to normal evaporation in the storage dewar is vented through the vent control solenoid. An in-line relief valve set at 4 psig and in parallel with the vent control solenoid valve allows the system to continue in case the vent control solenoid fails to operate. Vent gas from both the storage dewar and the cell dewar is available for cooling the optical cold shield.

G. Calibration Source

1. Requirements

The calibration source, which operates at a known temperature level and has an emissivity near 1.0, provides a known quantity of infrared radiation for calibrating the entire system. The temperature level is accurately maintained at the desired level by a temperature controller which is normally packaged as a separate unit. Ultimately the temperature should be held at the desired level within ±0.5°C or less; in the prototype system an accuracy of ±1.0°C is considered acceptable.

The calibration source temperature ideally should be adjustable over the entire operating range of the infrared measurements system (i. e. , ambient to approximately
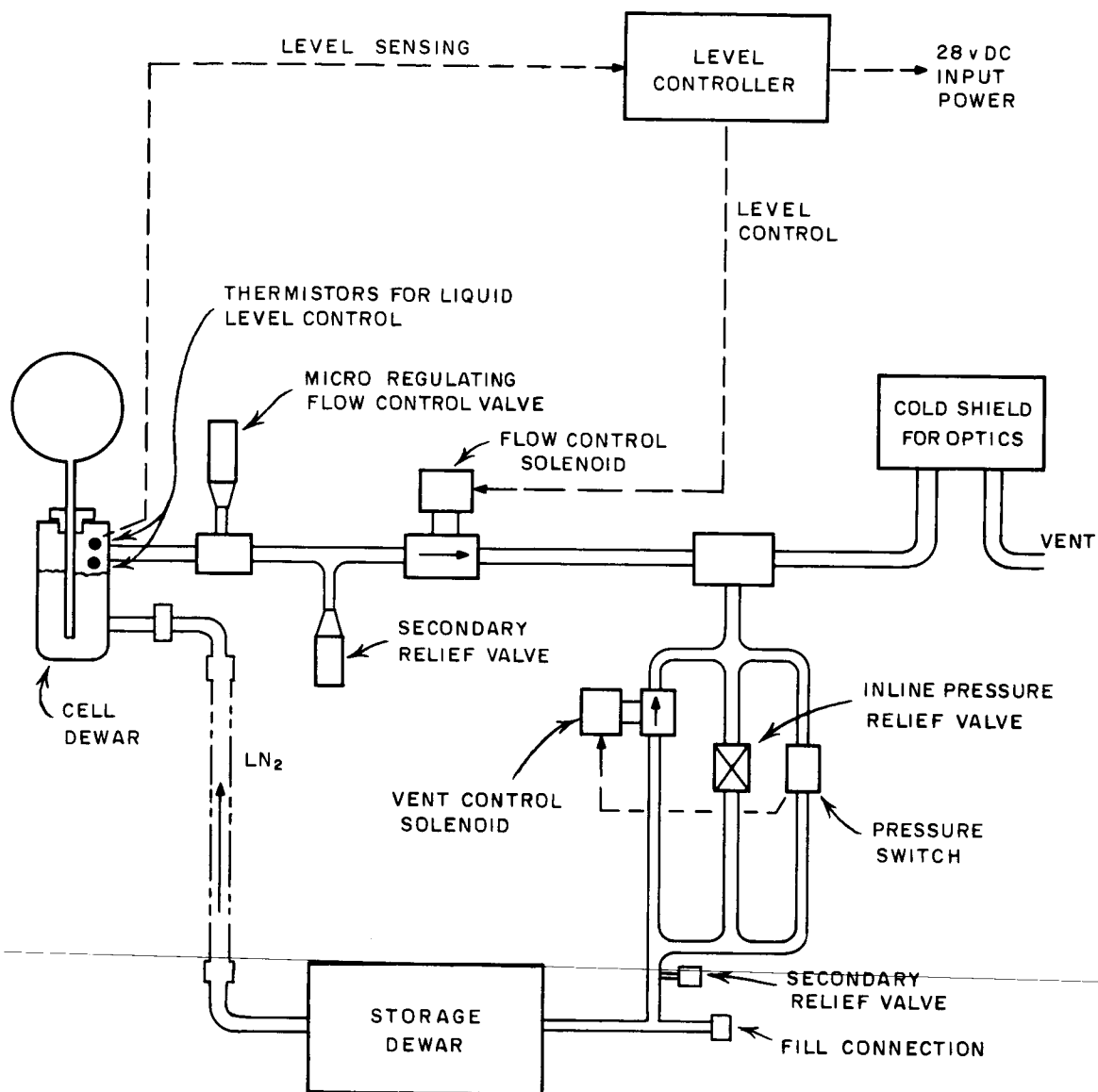
Figure V-36. Schematic of Cryogenics System

150°C). The higher temperatures are well within the range of available sources. However, these sources normally do not provide accurate control for temperatures ranging from ambient to about 20°C above ambient. One possibility for low temperature system calibration is to use the actual ambient temperature as a calibration point. An ambient "source" could be constructed by installing an accurate thermometer in a block of material with a high surface emissivity. When the "source" is viewed with the IR camera, system calibration adjustments would be used to obtain a readout corresponding to the thermometer reading. Inaccuracies resulting from using this "source" involve a nonunity surface emissivity and difficulties in measuring the true surface temperature.

Accuracy of the infrared measurements system may be improved by calibrating at two or more source temperatures. Changing the source temperature may be an unacceptable procedure because of the time required for the source to stabilize at the new temperature settings. To avoid this, two separate sources operating at different temperatures could be used. Another alternative is to operate the source at the higher calibration temperature and to insert optical filters to simulate a lower temperature.

To illustrate this technique, it was assumed that an equivalent source temperature of 300°K was to be simulated using a source operating at 400°K and two appropriate filters. One filter, whose attenuation varies with wavelength, was chosen to simulate the characteristic shift in blackbody spectral distribution with temperature. A second filter, with neutral density characteristics, was assumed to have a constant spectral transmission of 10 percent. The spectral transmission curve for each filter is shown in Figure V-37. A number of alternative filter combinations could have been determined which would simulate the source temperature of 300°K or other desired levels.
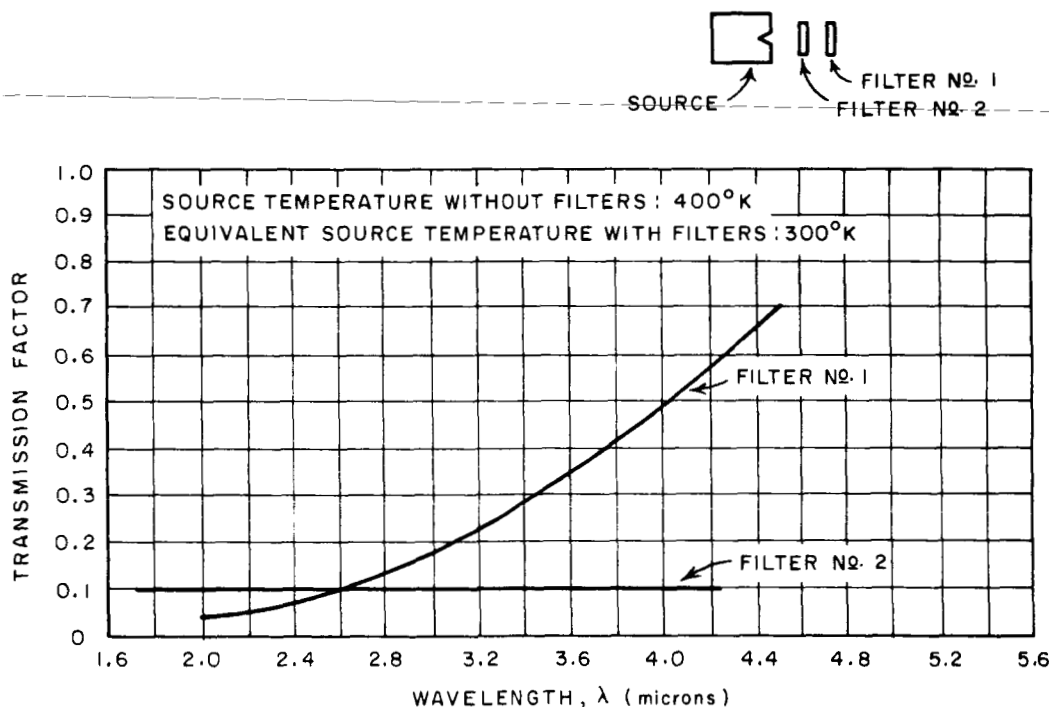

Figure V-37. Filters for Simulation of Calibration Source Temperature

The minimum aperture size for the calibration source was determined taking into account the smallest usable image on the IR vidicon retina and the lowest value of optical magnification. A minimum image size of 0.03-in. diameter was chosen since it would adequately cover the retina area of 0.02×0.02 in. corresponding to the minimum size of the readout gate. The lowest value of optical magnification is 0.05 for lens 1 and an object distance of 5 ft. The minimum diameter of the source aperture is then $0.03/0.05 = 0.6$ in.

2. Recommendations

Calibration source requirements are closely met by the Barnes Engineering Company model 11-101 source and temperature controller. Pertinent specifications for this unit are as follows:

Temperature range: 20°C above ambient to 230°C

Temperature accuracy: $\pm 1.0^{\circ}$C*

Maximum aperture diameter: 0.625 in.

Emissivity: 0.99 ± 1 percent

Source size and weight: $4 \times 3 \times 5\text{-}1/2$ in.; 2 lb

Controller size and weight: $9\text{-}3/8 \times 16 \times 9$ in.; 18 lb

For use with the infrared measurements system the source is mounted on a lightweight tripod as illustrated in Figure V-2 so that it can be easily positioned in the camera field of view. A 30-ft cable connects the source to the temperature controller mounted in the electronics rack.

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*Temperature accuracy can be improved by using a constant-voltage line transformer or by monitoring the actual source temperature with a thermocouple. However, these techniques are not required for the prototype IR measurements system.

VI. CONCLUSIONS

1. Use of an IR vidicon camera system to provide a real-time visible display of the thermal pattern of many electronic circuits and components is definitely feasible with presently developed equipment.

2. Temperature measurement with the IR vidicon camera is also a feasible concept with a more sophisticated system. Accuracy and breadth of application of a system of this type will depend on the quality of the infrared imaging tube as well as the performance of the other system components such as the IR optics.

3. The present capability for real-time thermal measurements is made possible by comparatively recent developments of IR imaging tubes with higher sensitivity. However, the imaging tube is still considered to be the limiting component in the performance of the overall measurements system. It is therefore expected that wider applications of the real-time measurements system concept will become possible as further improvements in image tube performance are realized. (Refer to Volume II of this report for a discussion of various system performance factors which are affected by the IR image tube.)

4. Optics adequate for an infrared measurements system can be designed and built. However, relatively sophisticated optical designs are required to avoid compromising the overall system performance.

5. Reductions in system performance for low differentials in scene temperature can be expected for optical systems with higher magnification factors. In this study the lens for microcircuit imaging uses the highest magnification factor. Its magnification factor of 4.8 reduces the effective irradiance level by 33.6/1. Consequently the ability to measure low temperature differentials is definitely reduced. (Refer to Volume II for specific expected performance of the system using a microscope optic.)

6. Alignment and focusing of the IR camera prior to energizing the circuit to be tested are best accomplished using a visual, reflex type of sight as described in section V. E.

7. Use of an all-electronic gating technique in conjunction with the signal processing circuits provides an excellent degree of flexibility for obtaining a temperature readout of a small portion of the scene. The feasibility of this concept for use with TV video signals has been verified experimentally.

8. Averaging techniques are able to enhance signal detection for low S/N ratios using readout speeds of from 5 to 10 seconds. With higher S/N, or if reduced accuracy is acceptable, readout can be much faster. It should also be noted that discernible changes in the thermal image are sensed and displayed on the TV monitor at the rate of 30 frames per second.

9. Direct conversion of signal level to temperature appears feasible using relatively sophisticated circuit designs and calibration procedures.

VII. RECOMMENDATIONS

A. Alternative Prototype Configurations

The various items which comprise a real-time infrared measurements system have been described in section V of this report. These items and possible sources for each are listed in Table VII-1. The sources are listed only as a guide since an equivalent item may also be available from other manufacturers. Several alternative configurations are possible in a prototype system, depending on the degree of sophistication desired.

1. Minimum System

This system would include only those items needed for limited experimental investigations of infrared concepts. These items are as follows:

a. IR TV Camera

1. Camera head with attached 2-hour cryogenics unit mounted on a base plate.

2. One Z-7808 IR vidicon tube.

3. Rack-mountable camera electronics control unit.

4. Interconnecting cables, 25-ft length.

b. Infrared Optics

1. One lens with 1-ft diameter field of view at object focus distance of 1 ft.

2. Reflex focus and alignment sight.

3. Cold-shielded lens housing.

c. Signal Processing and Display

1. One positionable video gate generator.

2. One video signal level detector with output suitable for digital voltmeter indicator.

3. Rack-mountable 17-in. television monitor.

d. Blackbody Calibration Source

2. Recommended System

This system is recommended because it is believed to represent the best balance between overall cost and feasibility for a prototype infrared measurements system. It consists of the same units as the minimum system described above, with the following changes and additions:

TABLE VII-1

	Item	Possible Source(s)	Model
	RECOMMENDED ITEMS FOR THE INFRARED MEASUREMENTS SYSTEM		
1.	IR Vidicon Camera	General Electric	UAR-252
	IR Vidicon Tube	General Electric	Z-7808
2.	Optics		
	Lens 1	Servo Corp. of America Diffraction Ltd. Perkin-Elmer	Special design
	Lens 2	Servo Corp. of America Diffraction Ltd. Perkin-Elmer	Special design
	Reflex sight	Wollensak Corp. Bell & Howell Corp. Eastman Kodak Co.	Special adaptation of existing design
3.	Cryogenics System	Linde Corporation	Modified LNF-54A
4.	Calibration Source	Barnes Engineering Co.	11-101
5.	Signal Processing Circuits	General Electric	Special design
6.	Television Monitor	General Electric	4TH26B1
7.	Electronics Rack Enclosure with	Ingersoll Products Div. (Emcor)	FR126A
	Pull-Out Writing Surface	Ingersoll Products Div.	RS22A
8.	Blower	McLean Engineering Laboratories	2EB512A
9.	Heavy-Duty Tripod	Camera Equipment Co.	TR3
10.	Tripod Dolly	Camera Equipment Co.	D3
11.	Cradle Tilt Head	Houston-Fearless	MCH-3

a.   IR TV Camera. Same as 1. a above except that the camera head unit is mounted on a heavy-duty tripod with lock-wheel dolly.

b.   Infrared Optics. Same as 1. b, with the addition of one lens with 1-ft diameter FOV at object focus distance of 5 ft with a reflex focus and alignment sight and cold-shielded lens housing.

c.   Signal Processing and Display. Same as 1. c, with the addition of an electronic signal amplitude-to-temperature converter unit with output suitable for digital voltmeter indicator.

3.   Additional Optional Equipment

The following items represent equipment additions for use with the minimum or recommended systems which can increase the flexibility and utility of the prototype equipment.

a. Multiple Signal Readout. This is applicable to the minimum system. Ten individually positionable video readout gates are provided for simultaneous measurements on ten portions of the TV scene.

b. Multiple Temperature Readout. This addition is applicable to the recommended system. It provides ten individually positionable video gates and ten signal-to-temperature converters for simultaneous temperature measurements on ten portions of the TV scene.

c. Digital Display and Printer. This is applicable to both the minimum and recommended systems. A digital display of signal amplitude (Option a) or temperature (Option b) reading is provided with the facility of producing a printed record of the displayed data on a controllable time-sampled basis.

d. Multiple Digital Display and Readout. This will be applicable only in conjunction with Option a or Option b. It provides an individual digital display and printed record of each of the outputs of the multiple readout systems.

e. Infrared Microscope Lens. The infrared microscope lens is applicable to both the minimum and recommended systems. A reflective magnifying lens suitable for TV viewing of 1/8-in.-diameter microelectronic modules is provided. Magnification reduces performance at low temperatures compared to lenses in the recommended system.

B. Program for Continued Investigations of Real-Time Infrared Measurement Techniques

1. A prototype infrared vidicon measurements system should be built for experimental investigations of real-time IR measurement techniques.

2. Experimental data should be obtained to determine thermal profiles of circuits and components which have experienced malfunctions. This data should cover both transient and steady-state conditions.

3. The prototype system should be used to evaluate component coating materials applied to achieve uniform emissivity.

4. A reliability testing program should be conducted to determine possible correlation between early-life thermal characteristics and reliability of specific electronic components.

5. The prototype system should be evaluated for nondestructive testing applications such as IR inspection of welds, bonds, etc.

6. The results obtained using the IR measurements system should be evaluated to determine additional features which are desirable. These might include items such as additional readout gates or a special lens for viewing microcircuits.

7. New IR image tube developments which could provide improved performance of the IR measurements system should be evaluated periodically.